

CHAPTER - I.

REVIEW OF THE PREVIOUS WORK.

A. PLASMA DIAGNOSTICS METHOD.

The last decade has brought about enormous growth in efforts towards understanding the properties of a plasma. This growth has come primarily from two sources; the controlled thermonuclear research program and the space programme, both of which have lent support to many research fields with overlapping interests; instrumentation for plasma diagnostics, a field concerned mainly with measurement of plasma temperatures and particle densities has consequently developed to a great extent. Diagnostic methods now include a host of techniques such as interactions with electromagnetic wave, probes, particle beams, lasers and spectroscopy.

The most admirably suited and versatile method for obtaining knowledge of plasmas lies in their interaction with electromagnetic waves. Although plasma can support a variety of waves with frequency as low as the ion acoustic frequency, we concern ourselves here with frequency range such that only electron motions are important.

In the case of microwave diagnostics, the interpretation often is difficult and requires not only an understanding of the formal theory of electromagnetic interactions with plasmas, but also development of an intuitive skill in selecting meaningful simplifications. Many of the cases of wave propagation are much too complicated to permit exact formulation and solution.

Historically, the subject of microwave diagnostics is not new. The laboratory experiments of Van der Pol (1920) to demonstrate that charged particles have a large influence on electromagnetic wave propagation did much to settle an important controversy of the day, whether or not an ionosphere was responsible for distant radio wave propagation. His calculations of plasma conductivity and

refractive index yielded the same equations to be found for the Lorentz plasma, including a density dependent term that was later named the plasma frequency by Tonks and Langmuir (1929).

The improved microwave technology following world war II opened new expanses of the frequency spectrum. The pioneering theoretical, work of Margenau (1946) and experimental work of Biondi and Brown (1949) in developing resonant cavity techniques, rekindled interest in plasma measurements with electromagnetic waves. Faraday rotation measurements with waves beamed through controlled fusion plasmas, performed by R.F. Post and others in Berkeley in 1952, stimulated the development of microwave diagnostics as a standard measuring technique in project Sherwood research (Wharton et. al. 1955, Herald 1956). The wave propagation characteristics as a function of electron density, magnetic field, and direction of propagation have been studied by Allis, Buchsbaum and Bers (1963); Stix (1962). The problem of energy flow in an anisotropic, dispersive, lossy medium becomes exceedingly complicated. The problem in the plasma context is discussed at length by Budden (1961), Stix (1962) and Brandstatter (1963).

The electron density profile and the electron temperature can be inferred from probing with electromagnetic waves, the most common usage has been to measure the average electron density. Procedures for obtaining profile information have been developed by Mottey and Heald (1959) and by Wharton and Slager (1960). Wharton and Slager used only the magnetic field independent parallel polarisation case. Their data reduction procedure is to calibrate the peak electron density by means of the cut-off of a "low-frequency" wave and obtain information from the simultaneously observed phase shift of a "high-frequency" wave. Mottey and Heald (1959) , using different polarizations, calibrated the average density with the high frequency wave. Because of the

greater phase shift nonlinearity of the perpendicularly polarized wave near cyclotron resonance the multiple polarization technique, when applicable, is somewhat more sensitive. The Wharton Slager technique provides profile information only at the instants of time for which cutoff occurs; the Mottey and Heald technique is limited to situations where the cyclotron frequency is comparable to the plasma frequency and is accurately known.

For very low densities, the cavity perturbation method can be used for the measurement of electron density if the cavity can be incorporated into the plasma vessel. The conventional microwave method of measuring plasma electron density consists in introducing the plasma into a resonant microwave cavity and measuring the amount of detuning which the plasma causes. The amount of detuning to electron density and collision frequency are discussed by Rose, Kerr, Blondi, Everhart and Brown (1949). The conventional method is limited in its validity to relatively low concentration ($\sim 10^9 \text{ cm}^{-3}$). Following a theoretical development by Ferraro (1957) a method is presented by Buchsbaum and Brown (1957) where by much higher densities can be measured. The method is based on eliminating the effect of a.c. space charge on the probing microwave field. This is accomplished by ensuring that the electric field be every where perpendicular to electron density gradients. S.C. Brown (1959) discusses several modes which can be used for low densities with and without magnetic field and for high densities where $\omega < \omega_p$, where ω is the frequency of probing signal and ω_p the electron plasma frequency.

For $\omega \gg \omega_p$ & $\omega \gg \nu$ (ν is the collision frequency for momentum transfer) the TM_{010} mode gives a frequency shift resulting from the presence of the plasma such that

$$\frac{\Delta \omega}{\omega} \approx \left(\frac{\omega_p}{\omega} \right)^2 \frac{1}{1 + \nu/\omega} \quad (1.1)$$

which can be used with or without an axial magnetic field since E is parallel to B .

When the electron density is nonuniform inside the plasma, as is nearly always the case, the frequency shift may be expressed in terms of an average density \bar{n} and a geometry factor a , $\frac{\Delta\omega}{\omega} = -a\bar{n}$. The factor a , constant in time, is calculated for various geometrical conditions and the results tabulated or plotted by Olson (1957), Buchsbaum and Brown (1957). Electron temperature or more generally the electron velocity distribution can also be measured by electromagnetic wave probing. According to hot plasma theory effects arise at the second higher harmonics of the electron cyclotron frequency given by $\omega_{ce} = eB/m_e$. These effects are attributed to the finite size of the electron gyration radius. The quasi-transverse extraordinary mode has been employed at 70 GHz to verify the predicted resonance width and depth.

Lindley and Menab (1961) presented a microwave diagnostics for helium cesium plasmas (at pressures 40 to 700 mm. Hg. and temperature upto 3000° K). They used the theory of the interaction of an electromagnetic wave with a plasma for microwave diagnostic measurements. One of the simplest microwave diagnostic experiments is transmission attenuation measurement in an isotropic plasma. Two radiators are arranged so that the path between them passes through the region to be studied. When the plasma density in the path reaches a value high enough that ω_p approaches ω , the transmitted signal will be attenuated.

Transmission and reflection of short electromagnetic pulses ($\sim 10^{-9}$ sec.) has been used to determine the electron density. From analysis of the time shapes of the transmitted and reflected signals both depending on ω_p and observation of the transient ringing which approaches ω_p within a few cycles n_e can be determined within time smaller than 10^{-7} sec.

Keenan and Kelly (1964) developed a microwave diagnostic (technique) system which permits X-band (8940 Mc/sec) wave guide transmission in the TM_{01} mode through this plasma without appreciably loading the r.f. excitation coil. Simple slotted line probing techniques have been developed which are capable of measuring the point to point plasma densities with a high degree of accuracy in relatively dense plasmas using only a single microwave frequency.

Wharton and Gardner (1959) devised the microwave interferometer for the diagnostic measurement. It is particularly useful in measurements on transient plasmas. A more sophisticated interferometer is the "fringe-shift" interferometer (Heald, 1959). In this type the phase shift is plotted directly on the oscilloscope, and the effects of amplitude variations are discriminated against.

Gierke et. al (1961), Schluter (1961), Misitane and Tutter (1961) have measured the electron density in r.f. discharge by three different methods as a functions of r.f. level. The values of peak density and spatial distribution obtained are in reasonable agreement with optical and probe data as well as with microwave phase shift measurements across the plasma column.

Waves in plasmas are subjected to a host of resonances at which the refractive index goes to infinity such as at the ion and electron cyclotron frequency and at hybrid frequency. Much interest has been generated by the recent observation of such resonance effects in ionosphere resulting much theoretical work. Since such resonance involve B , the magnetic field and n_e , the electron density, a very useful diagnostic method is available provided the experimentally observed resonances are correctly related to ω_{ce} and ω_p when the transmission frequency is very near the cyclotron frequency and the collision rate is low, the plasma refractive index may be very high especially if the density is high. In low temperature laboratory plasmas, however, the collision rate is relatively high, and damping of the whistler mode is prominent (Heald 1960, Dallis & Weaver 1962) even at microwave frequencies. Slow wave propagation at frequencies close to the electron

gyrofrequency can occur in high temperature, low density plasmas, such as magnetic mirror compression experiments. Electron temperature can be measured from black body radiation measurements. In general, noise temperature (blackbody radiation) measurements made in dense, high collision rate plasmas yield electron temperatures in good agreement with those obtained by Langmuir probes studied by Knol (1951), Easley and Mumford (1951) or spectroscopically, by Harding et. al (1958). Even in high temperature plasmas, where the collision rates are too low to provide the thermalizing mechanism for electrons, the electrons are often found to have a Maxwellian distribution according to Gabor et. al (1955), and in many cases the electron temperatures inferred from microwave radiation intensities compare favourably with temperatures measured by other methods (Bellis 1958), Wharton 1959, 1961, Stix 1962). The cyclotron radiation spectrum contains harmonics, whose relative intensities are stray functions of the electron velocities. For thermalized electron temperatures typical of most plasma experiments, including controlled fusion, harmonic numbers of 3 or 4 are about the theoretical limit.

In several plasma experiments, nevertheless, harmonics as high as the 24th have been detected with relative intensities that have little to do with conventional cyclotron radiation theories. In the experiment of Landauer (1962) upto the 24th harmonic of ω_c was observed in a plasma generated by a P.I.G. discharge, a type of discharge that is notorious for various instabilities. In the experiment of Bazhanova et al. (1961), a spectrum of 10th harmonic of the ion gyrofrequency was detected in the cgra machine (Artsimovich, 1958, Golovin, 1959) having a high energy plasma density about 10^8 ions/cm³. The observations of 8 or 10 harmonics of ω_c by Fields et al. (1962) and Bekefi et al. (1964) were made in the positive column of a hot cathode arc discharge having $\omega_b \approx \omega_c$.

All of these observations were made by holding the frequency of the receiver constant and varying the magnetic field. Landauer (1962) used two frequencies at once, 54 Gc and 10 Gc, and found that in all cases the peaks occurred at slightly higher frequencies than multiples of ω_c , rather than being shifted downward. A typical spectrum is shown in which it is seen that the intensities of the first 18 peaks are essentially the same. Observations made with the antenna oriented with \mathbf{E} along the magnetic field even showed several harmonics, but with reduced amplitude. Landauer offers several qualitative explanations involving "quasirelativistic" electrons and high nonlinear refractive index, that partially explains the observed effects.

A theory given by Pistunovich and Shafranov (1961), also involving a very large refractive index due to resonance partly explains Landauer's and also Bazhanova's results in Ogra. A recent theory by Simon and Rosenbluth (1963) provides a reasonable fit to Landauer's results and, in part, to Bekefi's findings. Simon and Rosenbluth have calculated the harmonics and line shapes generated by particles making cyclotron orbits and collisions with walls and sheaths simultaneously. The broadening and shifting of low harmonic number peaks and the variations with plasma frequency agree well with Landauer's data.

A brief review will now be given of the different methods used for plasma diagnostics.

PROBES :

The simple single wire Langmuir probe is undoubtedly the most widely used diagnostic tool in plasmas even to day. Such probes, though indeed rather simple mechanically, are quite the opposite in regard to the theory of current collection. In fact in most probe applications with plasmas immersed in magnetic fields, rigorous theory does not exist. Nevertheless probes continue to receive wide use since they can yield measurements with a degree of localization difficult

to achieve by other methods. Even when operating in domains where approximations can not be made to reduce the theory to a tractable form, they provide relative measurements that show a great deal of the structure of the usual nonquiescent plasma.

The single probe characteristics rely on establishment of a firm plasma potential that serves as a reference for the probe voltage. In some discharges a good reference point does not exist and in others fairly large electron currents are drawn to establish the probe characteristics, which cause perturbation sufficient to alter the plasma conditions. The double probe system was proposed to alleviate this difficulty. Two probes are spaced sufficiently close to ensure uniform plasma in the intervening region. The probe system is allowed to float relative to the plasma so that no net current is drawn by the system. The resulting potential is the "floating potential" which is sufficiently negative with respect to the plasma to repel enough of the higher mobility electrons to maintain $I_e = I_+$ where I_e is the electron current and I_+ that due to ions.

Between the probes one places a bias $v = v_1 - v_2 > 0$. Positive current flows in the external circuit from probe-2 to probe-1. If the probe areas are such that $A_1 \approx A_2$ both probes are negative relative to plasma but V_1 is less negative and V_2 more negative. Thus more electrons flow to 1 and fewer to 2. For large positive V_1 , probe 2 will draw only ion saturation current while probe 1 collects just enough net electron current to cancel the ion current to 2. The double probe characteristics is thus symmetric when $A_1 = A_2$ and the total current to either probe can not be greater than the ion saturation current. This condition has the advantage of minimizing the plasma perturbation since the current flow is small; at the same time however only the electrons in the tail of the distribution enter the probe current.

The classical theory of probe measurements in gas discharge Langmuir (1923), Langmuir and Mott-Smith (1924) and Langmuir (1926) contains the basic assumption that the potential difference between a probe and the plasma in which it is immersed, is confined to a space charge region or 'Sheath' which surrounds the probe, i.e. it is postulated that the plasma outside the sheath, is unperturbed by the presence of the probe. However, during the course of their researches on the low pressure mercury arc, Langmuir and his colleagues found that the potential difference existing between the axis of the discharge tube and the wall was not entirely associated with the wall sheath. The effect of this field penetration of probe measurements was ignored until the study of Bohm, Hurhop and Massey (1949). The subject has been discussed by several writers (Boyd 1950, 1954, Wenzl 1950, Allen and Thonemann 1954).

Bohm et al (1949) showed that the ion current depends on the electron temperature, and not the ion temperature because the electron temperature determines the strength of the electric field which draws the ions towards the sheath. However, their theory does not deal with the potential distribution within the sheath, nor with the increase in ion current which is observed as a probe is made more negative. Allen, Boyd and Reynolds (1956) presented a treatment which gives potential distributions both for the plasma and the sheath, together with the positive ion current-voltage characteristics. This work presents a method suitable for the computation of the characteristics of electro static probes in case where collisions are negligible. The method is applicable only to probes of such symmetry that the charged particle orbits can be characterized in terms of explicit time independent constant of motion. Bernstein, Irving and Rabinowitz (1959) used spherical and cylindrical probes to the collection of positive ions. The method is completely self consistent and requires no a priori separation of the discharge into plasma and sheath.

They formulated the theory of spherical and cylindrical probes immersed in plasma of such low density that collisions can be neglected. Medicus (1956), Boyd and Twiddy (1959) developed the practical techniques for extracting and displaying the second derivative of current by voltage to the distribution function in connection to the theory of Mott-Smith and Langmuir (1926). A simple and accurate electronic device for reducing the probe data and displaying the results on an oscilloscope is described by Harp (1963). The circuit employs commercially available plug in amplifiers to provide maximum ease of construction and high accuracy is obtained with a minimum of calibration adjustments. The probe characteristics of electron and ion currents for single electrode (cylindrical and plain) and for two, three and four electrode plane probes are studied by Ionov and Tonlegrade (1964). They found that the most complete and correct data on electron and ion distribution in a plasma can be obtained using three and four electrode probes. A four electrode probe should be used when photo and secondary emission occurs under the action of fast particles i.e. when studying low density cosmic plasma. Application of a magnetic field B has the immediate effect of decreasing the ratio of electron to ion saturation currents. This ratio which for $B = 0$ is

$(T_e m_+ / T_i m_e)^{1/2} \approx 100$ can decrease by an order of magnitude when the magnetic field is such that the probe radius and Debye length are large compared to the electron Larmor radius r_e but still small compared to the ion Larmor radius r_i . Whereas the electron current that is normally available with $B = 0$ is that ^{due} to diffusion into a surface surrounding the probe of radius equal to one mean free path, electrons in the magnetic field can move into the probe only along the direction of the field. Electron motion along the field is essentially unhindered whereas across the field the diffusion coefficient is reduced (classically) by the ratio

$$D_+ / D = 1 / (1 + \omega_{ce}^2 \tau^2) \quad (1-2)$$

where

$$\omega_{ee} \tau \approx (eB/m) (1/n \sigma v)$$

is the product of the electron cyclotron frequency and mean collision time with ions or neutrals whichever is dominant. For even very low fields $\omega_{ee} \tau \gg 1$, hence classical diffusion varies as $1/B^2$ and becomes extremely small. Classical diffusion is seldom observed in practice, the cross field diffusion being given rather by Bohm expression which varies as T_e/B . Nevertheless electron collection is mainly along the flux tube of radius $a + r_e$ with diffusion across the entire tube boundary maintaining the particle flux.

When a steady uniform positive column of a low pressure discharge is acted upon by a longitudinal magnetic field the charged particles having velocity components in all directions, spiral about the magnetic lines of force. Because of their small mass, only the electrons are appreciably affected by magnetic field. The spiralling parallel to the axis of the tube between collisions reduces the radial diffusion of electrons and thus a smaller radial electric field is required to maintain the equality between the numbers of ions and electrons arriving at the non-conducting tube wall. Since their radial velocities are the same, the radial flow of both charges will decrease. A longitudinal magnetic field should thus reduce the electron temperature and the electric field in the column.

In an attempt by Tonks (1939) to formulate a quantitative theory, use was made of a theoretical result (Townsend 1915) for the effect of a magnetic field on electron diffusion in the absence of space charge. This result was confirmed in experiments with electron swarms for photo electric currents (Bailey 1930). It holds also also for larger currents ($\leq 10^{-6}$ amp.) when allowance is made for the space charge. Other experiments (Cummings and Tonks, 1941) with a positive

column in mercury vapour were inconclusive because of the difficulty of interpreting probe characteristics taken in the presence of a magnetic field. Davies (1953) used the spectroscopic method to investigate the influence of a magnetic field on the electron temperature in a low pressure positive column in cesium vapour. Instead of a large reduction, however, a small increase in the electron temperature was observed. The effect of a magnetic field on the loss of charges from a plasma to the walls of a closed conducting box has been shown by Simon (1955) to be controlled by currents in the plasma which are flowing essentially along the field and not by plasma oscillations as previously suggested. These arguments do not apply here because the plasma of a positive column is uniform in the direction of the magnetic field. Bickerton and Von Engel (1956) presented a probe (movable probe) measurement in a positive column in helium in longitudinal magnetic fields and the effect of such fields on the column is discussed theoretically. Bertotti (1961) developed a theory of probe characteristics in presence of a strong magnetic field. Vimant (1963) studied the Langmuir probe in presence of magnetic field. Nobata (1963) studied the characteristics of Langmuir probe in presence of a strong magnetic field. The mechanism of the collection of charged particles by Langmuir probe in a strong magnetic field has been theoretically investigated by him. The magnetic field is assumed to be sufficiently strong i.e. the electron cyclotron frequency exceeds the collision frequency of electron with neutral gas molecules, and he obtained the following results (1) When the length of the probe in the direction of magnetic field is larger than the average gyration diameter of electrons, the probe current is determined by the gyration diameter, whereas when the probe length is smaller, the probe current is free from the effect of magnetic field. Experimental results concerned with the saturation

electron current agree with the calculated values. From a 24 probe azimuthal Array Bol (1965) has produced a beautiful display of density fluctuations occurring for given operating conditions of the Etude stellarator.

MAGNETIC PROBES :

Magnetic probes have been treated by Lovberg (1959) who points out their widespread use in mapping current distributions in plasma accelerators and pinches. Small inductive probes immersed in the plasma will have voltages induced in them by changes in the local magnetic field, $\frac{dB}{dt}$ (Glasstone and Lovberg 1960; Colgate et al, 1958). Field sensitive elements, such as Hall current probes, may be made as small as 1 mm in diameter and grouped in X-Y-Z arrays to measure three-dimensional field configurations (Pollock et al 1960). Current density contours and the pressure of hydromagnetic instabilities in dense plasmas are measured by a linear array across current channels. The data can be displayed by rapid sampling. The out put voltage of the coil type probe may be integrated to yield the magnitude of field. The resulting signals are very small (depending on the integration time) and care must be used to avoid stray pickup. Hall probes have outputs of a volt or so, reponse times upto few megacycles, and are easily calibrated with a standard magnet. They are somewhat temperature sensitive.

Another kind of coil assembly that measures rates of change in enclosed current channels is the Rogowsky loop or girdle (Golovin et al, 1958; Cooper 1963). The assembly consists of two sets of coils, one arround the entire experimental region and the other around only the current channel or a part of it. The difference in induced voltage represents the currents not enclosed, such as wall currents. The coils may be segmented, with leads brought out separately, to indicate current profiles. It is shown by Bergland et al (1963) that in the

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design of magnetic probes for plasma field measurements, attention must be given to the space resolving power of the coils. A technique is described by them, which by mechanical means gives an exact alignment of the individual coils in a multiple probe without any need for further manual adjustment. Integration of the signals by means of transistorized Miller integrators placed at the probe end of the transmitting cables, gives a good signal-to-noise ratio. The described system has an overall sensitivity of 1 mV G^{-1} at an RC time of 8 ns, and the band width extends to over 2 Mc/s.

Various magnetic probe measurements have been carried out by Gilliers et al (1963) to investigate the behaviour of the plasma in a theta type discharge. With "balanced" probes the amount of trapped field at the second implosion could be estimated. This technique has been used to estimate the electron temperature.

OPTICAL AND INFRARED PROBING :

Probing by means of light beams is, in principle, very similar to microwave probing, and the bulk of the theory developed applies with the addition that the increase in refractive index due to the neutral background gas in high density plasmas must also be accounted for. The techniques differ somewhat, but numerous parallels can be drawn (Alpher and White, 1959; Ascoli-Bartoli et al, 1960).

Optical interferometers that are direct analogs^{ue} of the microwave interferometer are useful for dense plasma measurements. The Mach-Zehnder interferometer is an example (Ascoli-Bartoli et al, 1960). A monochromatic light source is required; the smaller the wavelength spread, the sharper the interferences. Optical masers, or lasers (Schawlow and Townes, 1958, Javan et al, 1961; Lengyel, 1962) intrinsically are excellent monochromatic source but, for transient events, it is difficult to achieve accurate timing without elaborate triggering arrangements.

The giant pulse technique is a method to achieve fast triggering. A number of pulsed and C.W. lasers are now available commercially (Serchuk, 1962), covering wavelength ranges from 6900 to $72,00 \text{ \AA}$ (7.2μ). Spark and arc light sources, followed by a filter (Billings 1951) or monochromator, are also useful for interferometers of medium resolution. Metal electrode spark sources can produce microsecond pulses of intense light, having jitter time of only a few nanoseconds. A filter accepts the desired line, rejecting the others as well as plasma generated light. The light from the source must be much more intense than that from the plasma, of course, at the wavelength of interest.

A $0.1\text{-}\mu$ sec recording of the interferences was obtained looking along the axis in the Scylla experiment at Los Alamos (Elmore et al, 1959), made with a giant pulse laser source. The high density compressed plasma shows up plainly in the center.

Continuous time resolution of one dimensional slice of an experiment can be made by scanning with a slit and rotating mirror as a transient plasma event is occurring in the chamber to obtain a streak interferogram (Bennet et al, 1960; Ramsden and Mclean, 1962). The fringes will be shifted up or down in a display identical to the zebra-stripe display. The trace shows evidence of the increase in refractive index due to neutral atom density, followed by a decrease due to the electrons. If white light is used the positive and negative deflection will show up in different colors, since the group and phase velocities will be different for the deflection due to electrons and that due to neutral atoms (Klein, 1963).

A similar optical arrangement is used for Schlieren photography, except that changes in refractive index are recorded as modulations of light intensity, rather than interference fringes. An experimental arrangement for studying shock waves is given by Lovberg (1963). The light source is a spark between tungsten electrodes

in nitrogen. The accurate timing necessary to follow the fast front is obtained by Kerr cell light shutter.

The greater sensitivity for plasmas of medium density is obtained in the far infrared. Golay cell and bolometer detector are useful at wavelengths all the way across the infrared to the microwave band, although their response times are of the order of a second. Nevertheless, some plasma experiments have been done at infrared wavelengths (Brown, 1962; Harding et al, 1961) with results that compare favourably with microwave results.

Optical Faraday rotation can be used to study dense plasmas in strong magnetic fields (Dougal 1963). The sensitivity increases in direct proportion to the density the path length and the magnetic field applied.

PLASMA WAVE AND RESONANT PROBES :

When plasma waves or oscillations are present, they may be detected with probes, space charge waves may also be launched with probes, but this method of launching tends to excite all modes. Langmuir type probes, having coaxial shields brought up near the collecting surfaces, are adequate for many measurements up to frequency of 1000 Mc/s (Bailey and Imelcus, 1955). A pair of small disc probes has been used successfully to measure ω_p in dilute plasmas (Young and Sayers, 1957) and, in fact, wire and disc probes were used in experiments that probably were the first microwave diagnostic measurements by Van der Pol (1920).

When a current collecting probe simultaneously has a large r.f. voltage applied to it, the nonlinear sheath characteristics cause rectification of the r.f. signal. The d.c. current is thus altered by a small amount. The r.f. electric field around the probe is maximum at frequency near the plasma frequency,

leading to an increase in the rectified direct current as the applied frequency is swept through the local plasma frequency (Takayama et al, 1960 Ikegami and Takayama, 1963). The probe, of course, perturbs the plasma and thus the frequency measured is slightly below the true plasma frequency.

Resonant probes fed by transmission lines (Levitakii and Shashuria, 1961), permit measurement of the plasma impedance, plasma density and guide wavelength. Probes loosely coupled to a tunable filter, such as a motordriven coaxial resonator (Malmberg et al 1963), permit rapid analysis of the frequency spectrum of oscillations picked up in plasma, or as a means to filter received signals. The movable probes were used for those purposes.

PARTICLE BEAMS:

Plasma measurement with particle beams has received relatively little attention, in view of the little information plasma beam interaction affords. If we exclude processes such as beam induced instabilities and measurement of plasma in electromagnetic fields the beam interacts not with the plasma as a whole but rather with individual constituents through binary collisions. Charged particle beams can be used in plasma when no magnetic field is present or if the plasmas are in open magnetic devices. Atomic beams are better suited for probing when confining magnetic fields are present, since plasma boundaries are better defined perpendicular to the field direction, and also since scattering by micro fields can be eliminated.

In electron-atom interactions, the relative collision velocity will nearly always depend on the electron distribution function. Ionization is the most easily detected interaction and crosssections for such events as functions of electron energy are now available for a host of atoms and some ions. Because of the

cross-section velocity dependence ionization rate coefficients $S_e = \sigma_c (v_r) \cdot v_r$ computed for Maxwellian velocity distributions, have strong electron temperature dependence for $T_e \leq eV_i$ the ionization threshold. At higher electron temperatures there is relatively little temperature dependence. For beam probing of electron temperature, one therefore requires separate knowledge of the electron density and a beam with an ionization threshold greater than the temperature to be measured.

Electron temperature measurements have been made on stellarator discharges with potassium beams of about 3 Kev. For typical stellarator discharges where $n_e \approx 10^{13}$ the large ionization cross-sections for heavier alkalis afford good sensitivity, whereas attenuation of helium beams of such energies would be extremely small. Since the potassium beam is detected by secondary electron emission, the beam current is modulated at 100 K Hz with band-pass detection to discriminate against emission from plasma ultraviolet light. From microwave measurements of electron density and potassium beam attenuation one can therefore solve for the electron temperature.

LASERS :

Lasers for plasma diagnostic measurement are becoming increasingly popular. The most vigorously pursued experiments of recent years involving plasmas and lasers have been efforts toward observation of Thomson scattering of the laser photons by plasma electrons. Although such experiments were always possible in principle, the smallness of the Thomson cross section ($\sim 6 \times 10^{-25} \text{ cm}^2$) required the introduction of lasers to yield sufficient scattered photons relative to background light and phototube-noise to give meaningful results.

The scattered spectrum depends on a parameter d defined as the ratio of Debye distance to the wavelength of the sinusoidal plasma density fluctuation. For $d \gg 1$ coherent plasma oscillation can exist that give structure to the scattered electromagnetic wave, the central line of scattered radiation has a width characteristic of ion Doppler broadening and has satellite lines separated from it by approximately the plasma frequency $\pm \omega_p$. Under these conditions the electron density can be inferred from ω_p . When $d \ll 1$ only a central peak of scattered radiation is observed with a width characteristic of electron thermal motion. Absolute intensity measurements can yield the electron density.

For hydrogen plasma d is given in terms of scattering angle θ as

$$d = 1.58 \times 10^{-13} \lambda_0 \left(\frac{n_e}{T_e} \frac{1}{1 - \cos^2 \theta} \right)^{1/2} \quad (1.3)$$

where λ_0 is the wavelength of the incident radiation in nanometers, n_e the electron density and T_e the electron temperature ($T_e = T_p$) in ev.

Within the last few years many experimental observations have been reported measuring the electron temperature and the density in plasma. Recently Kronast (1965), Buser (1966), Yoseli et al (1968) discussed its application in the field of plasma diagnostics.

Although it appears that the rewards are potentially great, Thomson scattering is a difficult experiment at best, requiring great care in minimizing the background signal. Ruby lasers operating in the giant pulse mode and delivering tens of megawatts of power are necessary to resolve the scattered signal.

In the study of plasma properties lasers have extended to another diagnostic methods, interferometric methods, based on measurement of the refractive index

of the plasma, with or without magnetic field. Many experimental observations has been reported (Gerardo & Berdayen, 1964; Nagata, 1966 ; Johnson, 1967; Fonsaine et al, 1967 and others) measuring plasma properties for the last few years.

RADIOFREQUENCY CONDUCTIVITY METHOD:

The study of the electrical discharge phenomena in the steady state by means of a radiofrequency signal as a probe was first suggested by Vender Pol (1919). If a radio frequency voltage, not sufficient to cause the breakdown, be applied to an ionized gas, then the r.f. current $I_{r.f.}$ that flows through the gas is given by

$$I_{r.f.} = \frac{e^2 n X_0}{m} \left[\frac{\nu_c}{\nu_c^2 + \omega^2} - j \frac{\omega}{\nu_c^2 + \omega^2} \right] \quad (1.4)$$

when n is the number of electrons per cc of the ionized medium, e and m , the charge and mass of the electron respectively; $X_0 e^{j\omega t}$ the applied r.f. field; ω the angular frequency of the applied field; ν_c the collisional frequency of the electrons.

Hence the complex conductivity σ_c is given by

$$\sigma_c = \frac{I_{r.f.}}{X_0} = \frac{e^2 n}{m} \left[\frac{\nu_c}{\nu_c^2 + \omega^2} - j \frac{\omega}{\nu_c^2 + \omega^2} \right] \quad (1.5)$$

and assuming $\sigma_c = \sigma_r - j \sigma_i$

$$\text{so that } \sigma_r = \frac{e^2 n \nu_c}{m [\nu_c^2 + \omega^2]}$$

$$\text{and } \sigma_i = \frac{e^2 n \omega}{m [\nu_c^2 + \omega^2]}$$

It is thus seen that both σ_r and σ_i are functions of (i) frequency ω , (ii) electron density n , (iii) the collision frequency ν_c which is itself a function of pressure. The value of σ_r is maximum when $\nu_c = \omega$ in which case $\sigma_r / \sigma_i = 1$

Thus by measuring the conductivity of an ionized gas in a high frequency field the electron concentration can be obtained. The conductivity of ionized air was measured by Childs (1932) by substitution of a resistance of known value for the leakage resistance of the ionized gas, the oscillation frequency being 1 Mc/s. Appleton and Chapman (1932) studied the variation of the radiofrequency conductivity of ionized air with pressure at frequencies of the order of 1000 Mc/sec. using a Lecher wire system coupled to the condenser within which the discharge tube was placed, the radiofrequency current being rectified by means of a galena crystal and detected by the galvanometer. As the conductivity increases, the galvanometer deflection falls and Appleton and Chapman observed that the conductivity attains a maximum value at a certain pressure and then decreases in accordance with the theory; but they have not reported any absolute value of the conductivity for the gas investigated, namely air. Similar study was made in case of sulphur dioxide and xenon by Isam and Khashtgir (1937) in the pressure range 10 - 120 cm. of mercury using radio waves of $\lambda = 481$ cm. and a Lecher wire system.

The simple theory outlined above has been modified by Margenau (1946) by taking into consideration the distribution of velocities and employing Boltzman transport equation. The modified expression for σ is given by

$$\sigma = \frac{4}{3} \frac{n e^2 \lambda_e}{\sqrt{2 \pi m K T_e}} \cos \omega t + \frac{n e^2 \lambda_e \omega}{3 K T_e} \sin \omega t$$

for values of $\nu_c \gg \omega$ (1.6)

Later on several authors developed the theory considerably

Dawson and Oberman (1962, 1963) have developed an elementary model to calculate the high frequency electrical conductivity of plasma. H.L.Berk (1964) showed how the plasma model of Dawson & Oberman can be adopted to yield a kinetic description of electrical transport processes, which is uniformly valid for high and low frequency theories, as well as for finite wavelengths.

The theory of the electrical conductivity of a gas which is either fully ionized or weakly ionized has been well established for a number of years. Although the conductivity of a partially ionized gas is qualitatively well understood, very little quantitative information exists, principally because of the mathematical complications which arise when the electron-electron interaction is included in the Boltzmann equation for the electron velocity distribution function. Recently Johnson (1967) calculated the electrical conductivity for a variety of assumed electron-molecule collision frequencies. The results differ by only a few percent from those obtained using an approximation suggested by Frost. A simple procedure, requiring no numerical integrations has been given relating electron temperature to electrical conductivity for a partially ionized gas. Sen and Ghosh (1966) studied the properties of ionized gases experimentally by using radiofrequency probe. The radiofrequency conductivity (σ_r) of the ionized air, and nitrogen has been determined at various pressures and also at various values of discharge current. They observed that σ_r increases with pressure and attaining a maximum value gradually decreases. The maximum value of σ_r occurs at the same value of pressure for different discharge currents for the same gas.

Nagata (1966) presented a simple technique for measuring the plasma conductivity. The method is based on the observation that Hall current and Hall voltage are related simply to an electrical resistance. This method may also be applied to the measurement of electron density in high pressure plasma. An improved probe method of measuring the electrical conductivity of low temperature plasma is set

out by Khozhablev and Yarin (1966). They presented experimental data regarding the effect of layers near the electrodes on the probe readings. Recently Ciampi and Talini (1967) measured the average plasma conductivity by a r.f. probe, for a cylindrical plasma assumed radially inhomogeneous. They obtained the average conductivity value from 75 to 100 mho/m with a Q factor measurements from .5 to 1.5 MHz. The probe used is calibrated with electrolytic solution (H_2SO_4) of standard conductivity.

From a study of the complex conductivity of mercury vapour at microwave frequencies Adler (1944) has shown plots of σ_r and σ_i with current or pressure when the other is fixed. Using the theoretical expression of Margenau, Adler calculated values of the electron density in the discharge space and compared the values thus obtained with those obtained experimentally using Langmuir probe measurements. Adler found that the theoretical and experimental values agree closely and that σ varies linearly with the discharge current. Recently Aleksandrov and Yalsenko (1965) studied the complex conductivity of neon plasma by the Q meter method. The results are given regarding measurements of the active and reactive components of the conductance of the parallel-plate capacitor containing between its electrodes the plasma of a positive gas discharge column. The frequency range was .5 - 25 Mc/s, the discharge currents were 5 - 100 mA, and various gas pressure were used. Experimental results are in good agreement with the theoretically calculated values.

EFFECT OF MAGNETIC FIELD ON THE CONDUCTIVITY OF IONISED GAS.

Since the presence of a magnetic field changes the various characteristics of a discharge, it is natural to suppose that the conductivity of an ionized gas will also change in presence of a magnetic field. Conductivity of ionized gases

such as air, nitrogen and hydrogen in a magnetic field was measured by Ionsecu and Mihul (1932) for pressure greater than 10^{-3} mm. of Hg. who found that maxima other than those due to free electrons could be obtained. With very intense fields, only the vibration due to free electrons remained, the others disappearing and the values of the magnetic field giving maximum conductivity varied with pressure. A theory regarding the variation of radiofrequency conductivity with magnetic field was proposed by Appleton and Bochariwala (1935) who showed that the real part of radiofrequency conductivity in a magnetic field is given by

$$\sigma_{rH} = \frac{ne^2}{m} \frac{\nu_c (\omega^2 + \omega_b^2 + \nu_c^2)}{(\omega^2 + \omega_b^2 + \nu_c^2)^2 - 4\omega^2\omega_b^2} \quad (1.7)$$

where n is the number of electrons per unit volume and ν_c the collision frequency, ω is the angular frequency of the applied field and $\omega_b = eH/m$. A general theory regarding the variation of radiofrequency conductivity of ionized gases and its variation with pressure and magnetic field has been worked out by Gilardini (1959) who derived the expression for the conductivity of an ionized gas under the following assumptions :

- (a) When the distribution function is predominantly spherically symmetrical in velocity space but not necessarily Maxwellian.
- (b) When the electron collision frequency is an arbitrary function of electron velocity. The value of the complex conductivity is given by

$$\sigma = \frac{e^2 n}{m} \cdot \frac{1}{\nu_c + j\omega}$$

In presence of magnetic field he defined two conductivities; a conductivity σ_c for the right handed polarization and a conductivity σ_o , for the left handed polarization where

$$\sigma_c = \frac{e^2 n}{m} \cdot \frac{1}{\nu_c + j(\omega - \omega_b)}$$

$$\sigma_0 = \frac{e^2 n}{m} \frac{1}{\nu_c + (\omega + \omega_b)}$$

and the conductivity in the direction of the field is given by

$$\begin{aligned} \sigma_H &= \frac{1}{2} (\sigma_c + \sigma_0) \\ &= \frac{e^2 n}{m} \left[\left\{ \frac{\nu_c}{\nu_c^2 + (\omega - \omega_b)^2} + \frac{\nu_c}{\nu_c^2 + (\omega + \omega_b)^2} \right\} \right. \\ &\quad \left. - j \left\{ \frac{\omega - \omega_b}{\nu_c^2 + (\omega - \omega_b)^2} + \frac{\omega + \omega_b}{\nu_c^2 + (\omega + \omega_b)^2} \right\} \right] \\ \sigma_{rH} &= \frac{e^2 n}{m} \left[\frac{\nu_c}{\nu_c^2 + (\omega - \omega_b)^2} + \frac{\nu_c}{\nu_c^2 + (\omega + \omega_b)^2} \right] \end{aligned}$$

and after simplification it reduces to the result obtained earlier by Appleton and Bocheriwalla.

Later on several authors (Wu, 1965 ; Oberman and Shure, 1965; Schweitzer and Milohner, 1967; Green et al, 1965) studied the ionized gas in presence of magnetic field and developed the theory considerably.

Recently the complex conductivity of a plasma in a steady magnetic field has been studied by Pradhan & Das Gupta (1967). They have derived an expression for the complex conductivity tensor of a homogeneous classical plasma in an external uniform magnetic field using the Kubo theory of transport phenomena and have obtained exact relations between the conductivity tensor in the presence of the magnetic field and in its absence.

B. ELECTRON MOBILITY IN MAGNETIC FIELD.

The pioneering work regarding the mobility of electrons in various gases was done by Townsend and his coworkers (Townsend & Tizard, 1913). Notwithstanding the revived interest in the measurement of transport coefficients for low energy electrons drifting and diffusion through gases at pressures ranging from several torr to several hundred torr (Mc Daniel references therein 1964) little work has been done to add to this early work of Townsend and its extension by his colleagues to a number of other gases (Healy and Reed 1941 and references therein; Townsend 1948).

The early experiments were designed specifically to measure the drift velocity and the data determined from them were unique for many years. In fact, because of fundamental limitation to time of flight methods the only available data for electron drift velocities at high values of E/p (ratio of electric strength to gas pressure) are those derived from experiments of this type. However, as has long been realized (Townsend 1937) there are difficulties in deducing precise values of drift velocity from these measurements. When the method was first applied, Townsend deduced a simple relation between the angular deflection of the stream of electrons and the drift velocity by assuming, as one of several simplifications, that all electrons in the swarm have the same agitational speed. Subsequently it was shown (Townsend 1937) that, if proper account were taken of the distribution of speeds within the swarm, the drift velocities deduced from the simple formula has to be multiplied by a factor nearly equal to unity the magnitude of the factor depending on the form of energy distribution assumed. Because of these difficulties of interpretation it is not surprising that the earlier method was superseded by the more direct time of flight techniques first used for electrons by Bradbury and

Nielsen (1936). Although the limitations to the accuracy of the data obtainable with these techniques have not always been appreciated (Duncan, 1957; Lowke, 1962) it is in most circumstances possible in principle to produce data of high accuracy, whereas the method of magnetic deflection is susceptible to certain percentage of error.

With few exceptions (eg. Huxley 1958, Hall 1955) the method has been abandoned for the measurement of electron and ion mobilities but an attempt was made by Huxley and Zaazou (1949) to exploit the technique as a means of investigating the distribution of electron energies in swarm experiments. At that time, as has already been pointed out, it was realised that the true drift velocity U_d could be obtained from the drift velocity U_M measured by a magnetic deflection technique only ^{by} multiplying it by a dimensionless factor. Consequently in their paper Huxley and Zaazou (1949) compared electron drift velocities measured by Bradbury and Nielsen (1936) with values of U_M measured by a new method based on Townsend's original method and from this comparison drew some conclusions regarding the energy distributions of the electrons in the range of E/p values over which the comparisons were made.

Subsequently, Huxley (1960) derived a rigorous relationship between U_d and U_M and showed that the coefficient C in the relation

$$U_d = C \cdot U_M \quad (1.8)$$

depends directly on the variation of the momentum transfer cross section with electron energy, as well as indirectly through its effect on the distribution of electron energy. The theory and mechanism was however further studied by many workers. Frost and Phelps (1962), Engelhardt, Phelps and Risk (1964), Jory (1965), Elford (1966), Compton, Elford and Jory (1967) and others.

The effect of magnetic field on the mobilities of charged particles has been studied by Townsend and Gill (1938) who showed that the mobility of the charged particles in the direction of the field H is reduced and is given by

$$\mu_{eH} = \frac{\mu_e}{1 + \omega_e^2 \tau_e^2} \quad , \quad \mu_{iH} = \frac{\mu_i}{1 + \omega_i^2 \tau_i^2} \quad \dots (1.9)$$

and $\omega_e = eH/m_e$ $\omega_i = eH/m_i$

where μ_e is the mobility of electrons in the absence of magnetic field, e the electron charge, m_e the electron mass, ω_e the gyrofrequency of electrons and τ_e the collision time between electrons and neutrals. The same notations are valid for ions where i is used as subscript. Eblein and Haydon (1938) considering the bulk properties of electron avalanches have deduced that

$$\mu_{eH} = \frac{\mu_e}{1 + C_1 H^2 / P^2} \quad (1.10)$$

where $C_1 = [eL/mu]^2$; L denoting the mean free path of the electron in the gas at a pressure of 1 mm. of mercury and u denotes the random velocity of the electron in the gas. It can easily be shown that equation (1.9) reduces to equation (1.10) if a simple calculation is carried out. The determination of electron mobility in presence of the magnetic field will indicate the interaction of the field with the motion of the electrons and will enable us to verify the theoretical expression deduced by Townsend and Gill (1937) and Eblein and Haydon (1938). Further in case of breakdown of gases excited by radiofrequency voltage the loss of electrons has been ascribed to mobility of the electrons and hence in presence of magnetic field the determination of mobility coefficient will enable us to calculate the breakdown voltage theoretically.

The measurement of electron mobility in presence of magnetic field becomes difficult as the mobility of charged particles itself is measured by magnetic deflection method. The present authors have studied the mobility of electrons in presence of magnetic field by two different (rather indirect) methods and verified the theory given by Townsends and Gill (1938) and Ebevin and Haydon (1958).

LOW TEMPERATURE PLASMA DIFFUSION IN MAGNETIC FIELD.

Ordinary diffusion of electrons and ions across a magnetic field is caused by collisions. The classical binary collision diffusion theory (normal diffusion theory) which is based upon the equation of motion of charged particles is Boltzman's equation, ^{which} predicts a greatly reduced diffusion rate in the direction across a strong magnetic field. The theory has been confirmed by experiments with low temperature plasmas, only under restricted conditions.

The development of this subject during the past decade has been highly influenced by the pioneer work of Bohm, Barkop, Massey and Williams and their collaborators (1949).

Earlier reviews of this topic have been given by Simon (1958), ~~and~~ Lust (1960), by Paulikas (1962), by Hoh (1962), by Boeschoten (1964) and by Granovskii (1966). An extensive discussion on these problems is also due to Lehnert (1961).

The binary collision diffusion coefficient of charged particles perpendicular to a homogeneous magnetic field has been given by Townsend (1937)

$$D_{i\perp} = \frac{D_i}{1 + \omega_i^2 \tau_i^2} \quad ; \quad D_{e\perp} = \frac{D_e}{1 + \omega_e^2 \tau_e^2}$$

$$\omega_i = e H_z / m_i \quad ; \quad \omega_e = e H_z / m_e \quad (11)$$

where D_0 is the diffusion coefficient of ions in the absence of a magnetic field, e the electron charge, m_i the ion mass, ω_i the gyrofrequency of ions, and τ_i the collision time between ions and neutrals. The same notations are valid for electrons where e is used as subscript. Here we mainly confine the discussion to a weakly & singly ionized gas in which only collisions with neutral particles are important. A rigorous treatment of diffusion coefficients (equation 1-11) in such a gas has been given by Chapman and Cowling (1953). Golent (1960) has extended their calculation to include the effect of electron-ion interactions.

DIFFUSION IN ARC CHAMBERS :

An arc of some amperes is struck between the filament and the anode. Ionization takes place in arc column continuously, and the produced charged particles diffuse radially outwards. These form a secondary plasma body, having a temperature upto 2 eV, around the arc. In general, electron neutral and ion neutral collision dominate.

This secondary plasma body is kept in a steady state, partly by its diffusion along the magnetic field with subsequent recombination at the walls and partly by radial diffusion across the magnetic field. Obviously, the characteristic e-folding length λ_0 , by which the plasma density decays radially, depends upon the ratio between the diffusion rate of the secondary plasma along and across the magnetic field. The value λ_0 can be obtained by measuring the ion-density distribution with probes. With these values, the transverse diffusion coefficient of ions can be determined and compared to that given in equation (1-11).

A correct approach of the "Normal Diffusion Theory" seemingly simple, but in reality a very complicated, problem was first given by Simon (1953) and then by Zharinov (1960). A more detailed analysis of this problem has been

given by Tonks (1929), who approached the problem by assuming an approximate Boltzman equilibrium for the electrons along the magnetic field, but allowed a small deviation in the potential.

With a cylindrical geometry Neidigh and Simon (1959) were able to show that $X_0 \propto 1/H_z$ and that $X_0 \propto P_0$ is in accordance with the theory of Simon. At lower pressure, $X_0 \propto P_0^{1/2}$ was found in agreement with Tonks. As calculated from equation (1.11), Simon claimed a satisfactory agreement. Further, he found similar agreement from Bohm's data. Simon (1958) concluded that plasma oscillations have little effect on diffusion and that no drain diffusion mechanism need be proposed.

Later, Baeschten and Schwirzke (1961) studied the transverse diffusion of electrons and ions in a large drift tube inserted in a magnetic mirror field with a small mirror ratio. The dependence $X_0 \propto 1/B_z$ was found in agreement with the observation by Simon and Neidigh.

Instead of inserting probes into the plasma body, Zharinov (1960) mounted his probes outside the plasma. Through holes in the anode, electron and ion currents along the corresponding lines of force could be collected. He found that the electron currents to the probes were much larger than that predicted from the electron diffusion coefficient in equation (1.11). They also found that the electron probe current suddenly increased by an order of magnitude at a certain critical magnetic field, whereas the ion current remained unaltered.

DIFFUSION IN POSITIVE COLUMN :

In contradiction to the arc plasma, the radial density distribution in a cylindrical positive column immersed in a strong axial magnetic field is independent of the magnetic field. Nevertheless, the particle flux to the

wall greatly decreases as a consequence of equation (1.11). The reduced particle loss reflects itself in the diminished rate of ion electron pair production. This requires a lower electron temperature and decreased axial electric field. Thus, the transverse diffusion coefficient can be estimated from the measured axial electric field.

Schottky's theory of positive column has been extended by Tonks (1934) and by Bickerton and Von Engel (1956) to include the influence of an axial magnetic field. Later Lehnert (1958) rigorously re-examined various aspects of the theory, starting from the macroscopic equations of the motion of charged particles. The corresponding extension of Langmuir and Tonk's theory has been carried out by Bickerton and Von Engel, who also experimentally verified their theory. Hoh (1960) made the same initial assumptions as those listed by Lehnert, to write the basic equations in a suitable form.

The electron temperature necessary to produce the required ionization rate $\bar{z}(T_e)$ may be obtained from a relation given by Von Engel and Steenbeck (1955). On the other hand, the axial electric field E_z is also connected with electron temperature through the energy balance relation; i.e. the energy gain of an electron in the field E_z between two collisions should, on the average, compensate the energy loss of the electron in a collision. Denoting the average fractional energy loss of the electron in one collision by $K_e(T_e)$, it was found that

$$E_z = \left(\frac{64}{\pi}\right)^{1/4} \left[K_e(T_e) \right]^{1/2} \frac{k T_e}{e \lambda_e} \quad (1.12)$$

where λ_e is the electron mean free path. The above equation is plotted by using $K_e(T_e)$ function given by Lehnert (1958), and by Hoh and Lehnert (1960) and Wojcisek (1960). The diffusion coefficient D_{01} is now expressed as a function

of E_z via the functions $\zeta(T_e)$ and $K_e(T_e)$. Essentially the effect of an axial magnetic field B_z is to decrease D_{\perp} , T_e and hence, also E_z .

The use of the axial electric field as a measure of the radial diffusion has been criticized. Firstly, it has been pointed out that the axial electric field is a rather insensitive measure of the particle losses (Lehnert 1958, Ecker.G. 1961) secondly, both $\zeta(T_e)$ and $K_e(T_e)$ were calculated assuming a Maxwellian distribution of the electrons (Lehnert 1958, Von Engel 1955, Ecker 1961) ^{It} has been suggested that use of the radial-potential distribution provides a more sensitive method for the study of radial diffusion.

In spite of these facts, experiments with a helium positive column in a magnetic field showed good agreement with the theory. Actually, recent probe measurements in the experiments of Von Gierke and Wohler (1961) showed that the electron velocity distribution in a helium positive column is very nearly Maxwellian and does not change very much with the magnetic field.

Early experiments by Rohklin (1939), by Cunnings and Tonks (1941) and by Reichrudel and Spivak (1941) of the positive column in magnetic fields available were found to give results in agreement with the theories (Tonks & Langmuir 1929, 1939, Schottky 1924) later, Bickerton and Von Engel (1956) showed that the positive column behaves in accordance with the normal-diffusion theory in an axial magnetic field up to 500 gauss.

In extending these experiments to stronger magnetic fields and to longer tube lengths, Lehnert (1958) made the important discovery that the positive column suddenly became unstable and that the transverse diffusion increased greatly when the axial magnetic field exceeded a certain critical value.

Hoh and Lehnert (1960) measured the axial electric field by the probes, as a function of the magnetic field and when compared with the normal diffusion theory, the theory fits the experimental values ^e quantitatively upto a certain critical magnetic field.

The dependence of the critical magnetic field on the pressure, tube radius, different gases, and the end effects has been explored systematically (Hoh & Iehwert , 1960). From the currents collected by probes inside the plasma, Vasileva and Granowski (1959) found some kind of anomalous diffusion by using probe techniques.

With stereo-streak photographs, Allen, Panlikas and Fyle (1966) found that the current in the positive column concentrated in a rotating screw shaped channel when the magnetic field just passed its critical value. The rotational frequency and the wavelength of the helix, as well as the critical magnetic field measured thereby, were of decisive importance in checking and confirming the theoretical predictions made by Kadomtsev and Medvedev (1960). The critical field measured under various conditions was in good agreement with previous experimental results (Hoh & Iehwert 1960). Further, the radial potential observed also seems to agree with theoretical predictions (Hoh 1962, Johnson & Jerde 1962).

In a low pressure PIC discharge, Bonnal, Brifford, Gregoire and Manus (1961) found that the radial anomalous diffusion decreased again with increasing magnetic field at magnetic fields much larger than the critical field.

Further, no rotating screw shaped current channel was observed in contrast to other experimentals (Allen et al 1960, Johnson & Jerde 1962).

Von Gierke and Wohler (1961) have extended the experiments to include the effects of additional r.f. ionization (4 MHz), helical multipolar magnetic fields, and a pure azimuthal magnetic field. Johnson and Jerde (1962) studied the screw instability in a magnetic field that smoothly rose to its full value in a time of the order of few milliseconds. It was found that the critical magnetic

field observed was three times higher than the corresponding static critical magnetic field. They suggested that the rising magnetic field induced an azimuthal electric field which depressed the onset of the instability. Further, if the static axial electric field were replaced by an a.c. field (Paulikar 1961), the instability disappeared when the frequency of the a.c. field was higher than some tens of KHz . All these observations seem to be compatible with the screw instability theory (Kadantser 1960, Hoh 1961, 1962, Johnson 1962) although a detailed proof has not yet been given. The screw instability also seems to be operative in heavily distorted geometries (Ekman, Hoh and Lehnert 1960) and seems to be observed in connection with microwave measurements of the electron temperature of a positive column in magnetic fields (Brown et al 1962).

A new method for obtaining electron diffusion coefficient has been introduced by Just and his coworkers (1963) at the Oak Ridge National Laboratory. This method differs from Townsend's (1915) in that it requires pulsed rather than steady state operation. The technique differs from the Townsend and electrical shutter methods in that it permits the simultaneous independent evaluation of both the drift velocity and diffusion coefficient.

The theory and mechanism was however further studied by many workers. Granovskii & Urazakov (1964), Mouthaan (1965), Granovskii (1966), Schwirzki (1966), and others.

C. RADIATION FROM GLOW DISCHARGES.

The radiation emitted by gas molecules after excitation by collision has been the paramount source of existing knowledge about the internal structure of the gas molecules, about the environment in which the gas molecules exist, and about the stimulating collisions themselves. Radiation from gas discharges has supplied means of measuring atomic abundances, identities and chemical reaction rates. An understanding of the radiation from gas discharges rests on the elucidation of two separate stages in the process (1) the release of energy as radiation by the gas molecules and (2) the delivery of energy to the gas molecules. Each atomic or molecular species radiates a characteristic set of frequencies which are governed by the Planck relation

$$h \nu_{ji} = E_j - E_i \quad \dots(1.13).$$

The probability per unit time that such a transition will occur spontaneously in an atom excited to the j th state is given by

$$A_{ji} = \frac{64 \pi^4 e^2 \nu_{ji}}{3 h c^3} | \chi_{ji} |^2 \quad \dots(1.14).$$

where $\chi_{ji} (= \chi_{ij})$

is the matrix element of the dipole moment for the transition from E_j to E_i . Most commonly occurring radiations are dipole radiations, but transitions which are forbidden in dipole radiation by the identical vanishing of χ_{ji} can sometimes be observed weakly in quadrupole or magnetic dipole radiation with a

probability which is roughly in the ratio of $(a_j/\lambda)^2$ to that of an allowed transition. Here a_j is the orbital radius of the upper state. Extraneous fields can permit forbidden transitions also.

If the probability per unit time of spontaneous emission of frequency ν by a single radiator is known, it is in principle possible to compute the intensity of radiation. Low pressure gas discharges, despite the real complexity of their energy transfer processes, are simple to analyse when compared with the vastly more complex situation in terrestrial high pressure discharges or in stellar atmospheres whether at high or low pressure, these last being complicated by their vast extension over space. A working criterion for a low pressure gas discharge, from the optical point of view, can be that it should not appreciably reabsorb its radiations or in other words that spontaneous emission is its sole radiation process.

For those transitions which pass unhindered through the gas, the analysis of radiated intensity is straight forward. If N_j refers to the population of the j th excited state of the radiator, then the essential changes in this population will be brought about by radiative transition to lower states, radiative transitions from upper states, absorption of blocked ground state radiations, and collision interactions with other particles. Then a system of equations governs the energy level populations.

$$\frac{\delta N_j}{\delta t} = D_j \nabla^2 N_j + B_{0j} P N_0 - \sum_{i=0}^{j-1} A_{ji} N_j + \sum_{K=j+1}^{\infty} A_{Kj} N_K + P_j \dots(1.15).$$

where D_j is the diffusion coefficient for state j radiators, when j is one of those states which radiate to the ground state, then assuming that the diffusion treatment of blocked radiation is adequate, a second set of equation is needed.

$$\frac{\delta P}{\delta t} = D_j \nabla^2 P + h \nu_{j0} [A_{j0} N_j - B_{0j} P N_0] \dots(1.16).$$

where D_j is a photon diffusion coefficient defined as $c/3R$ where "c" is the velocity of light and R is photon absorption coefficient. Eliminating the absorption term between the last two equations and assuming that the gas density is large enough so that the photons spend much less time in the free state than in the radiators

$$N_j > P/h\nu \quad \text{where } P(\nu_j) = \text{monochromatic radiant energy density}$$

$P = \text{production function}$

One set of equations can be obtained as

$$\frac{\partial N_j}{\partial t} = D_j \nabla^2 N_j - \sum_{i=1}^{j-1} A_{ji} N_j + \sum_{k=j+1}^{\infty} A_{kj} N_k + P_j \quad \dots(1.17).$$

Elastation is the primordial source of all radiation from gas discharges. Radiators in any state may absorb the kinetic energy of impinging particles and go over into higher energy states with a minimum of restriction by selection between states for which the reverse radiative transition is allowed.

Experimental measurements of the cross sections with gas molecules offer to electrons for various exciting transitions have been carried out along two general lines. First, electrical measurements have been made of the fraction of electrons which have lost discrete amounts of energy. Second, optical measurements have been made of the number of photons of a given species emerging from a gas through which a known charge has passed. Both methods are difficult and the results have proved quantitatively discordant with each other and with theory whenever quantitative measurements have been possible.

There are different processes of excitation where the higher energy levels are populated. The electron impacts of the first kind is where electrons collide with other particles to give its excitation energy and the process is governed by the relation

$$\frac{dN}{dt} = \sigma N_1 N_2 \bar{u} \quad \dots(1.18).$$

where N_1 and N_2 are concentrations of colliding particles of both species, \bar{u} their mean relative velocity and dN/dt is the rate of production of the altered molecular state. Excitation by massive particle impacts have got radiation efficiencies extremely low compared to that of electron and it is easy to set up subsidiary processes involving impacts of free electrons which will mask the desired effects.

In the process of excitation by absorption of photons it is found as in the emission of radiation, the selection rules appear to govern its absorption rigorously. Apparent deviations have always resulted in the discovery of subsidiary process involving other systems. The role of volume recombination into excited states proved as having very minor effect both electrically and in the production of radiation at low pressure. Volume recombination of an electron, +ve ion and photon system and positive ion negative ion system may be looked upon as potentially leading to radiation. Volume recombination in any of its forms, while inconspicuous in active discharges, is the prominent and unique source of radiation from low pressure after glows. In complete generality, the problem of the flux of population of any one state must be dealt with by finding the fluxes for all states. In restricted cases however, it is possible to define a cascading coefficient which makes the general solution unnecessary. The restriction is fulfilled by

- (1) electron excitation from the ground state
- (2) recombination process
- (3) collisions of the second kind between foreign radiators and ground state particles, where the necessity that the original population of each state be derived from a source which is independent of the individual excited state populations is fulfilled. The process of cascading is important to spontaneous transition from the upper states of a radiator to the lower states which furnishes a significant portion, although not a major portion of population of each state.

The chief process of depopulating levels is almost invariably spontaneous emission. Collisions of the second kind are also a depopulating process as well as a populating process. Sometimes the result of the collision is an exchange of

states in which both populating and depopulating processes figure. Rossler and Schonherr (1938) studied the radiation of Hg ($6^3P_1 - 6^1S_0$) as a function of pressure and current and identified both pressure and current dependent losses which they attributed to collisions of the second kind with neutrals and electrons respectively. At large densities many workers have observed that a marked decrease sets in in the intensity of radiations from discharge. This is specially true of the inert gases. In helium this decrease sets in at approximately 2.5 mm. Hg. Mayerott (1944) opened the way to an understanding of this process by the suggestion that the population of He_2 and He_2^+ and presumably other molecular ions might be larger than previously estimated. Bates (1950) suggested that the large microwave recombination coefficients could be understood as dissociative recombination with He^+ . Phelps and Brown (1952) isolated large quantities of He^+ from helium discharges at 5 mm. Hg. pressure but found little at 1 mm. Hg. Hornbeck and Molnar (1951) suggested that the appearance potentials of molecular ions in noble gases could not only be explained by the existence of collision process of the second kind in which excited helium atoms formed molecular ions upon collision with neutral atoms. Fowler and Duffendack (1949) had proposed an unidentified process of the second kind as one possible cause of the intensity decrease but discounted the possibility because of the supposition that it would require degradation of the entire excitation energy in the kinetic form, in defiance of the Franck-Condon principle. The dependence of the intensity of the spectral lines upon the tube current was investigated at both high and low gas densities holding tube potential constant. The relationship was found to be linear within the experimental error between the extremes of 1.4×10^{14} and 2.5×10^{16} atoms/c.c. This relationship was observed for all types of transitions and over a current range from one to one hundred mA. This has been further extended by the work of Lees who reports a linear dependence existing as low as 0.2 mA for all transitions. Spectral

intensities as a function of gas density of particles per unit volume were investigated over a wide range of density extending from 2×10^{13} to 1×10^{18} molecules/c.c. holding tube current and potential constant. All the density vs. intensity curves have essentially the same form, rate of decay and location of the maximum. One outstanding exception is found in the $2^3P - 3^3D$ transition which had a broader maximum and slower rate of decay than the others. The maximum was located at about 15mm. Hg. pressure about five times the value found for other transitions. Since this transition corresponds to 5875 Å, the anomaly leads to a pronounced color change in the discharge between high and low pressures, the high pressure discharge being yellow, while the low pressure discharge is bluish green. Measurements have been made of the intensity of radiation from the low voltage arc in helium as a function of gas density, tube current and tube potential. The experimental results indicate that the radiation is the result of a primary electron process. This process has been generally assumed to be direct excitation. Such an explanation is not fully in accord with the phenomena observed and so possibility of an unrecognised process has been suggested.

Little or nothing has been reported about the radiation from Townsend discharge. Griggs and Joffe (1947) indirectly showed the presence of high energy photons in this type of discharge. If β_j is the number of excitation to state j per unit length of electron path defined as

$$\beta_j = \frac{N_0 \int_0^\infty \sigma_j u^3 \phi(u) du}{U \int_0^\infty u^2 \phi(u) du}$$

...(119).

where U is the drift velocity for electrons in the electric field present, and $\phi(u)$ is the electron distribution compatible with the field, then the energy of radiation in a transition ν_{ji} is given by

$$h \nu_{ji} A_{ji} \frac{\beta_j}{\alpha} (e^{d \times} - 1)$$

per avalanche of length λ . From this basic expression the power radiated can be calculated in the various eventualities which may arise.

The radiation property of the monoenergetic electron discharge was studied and utilised for different purpose of measurements. Maxwell (1928, 1930, 1931, 1932) found that it was possible to detect the life times of ionic excited states by sidewise shift of their radiations in the applied electric cross field. Intensity variation of the spark lines due to the motion of the positive ions was the main problem of observation. Spark lines due to singly and doubly charged ions show a variation of intensity along their length in such a manner that it is possible to distinguish them from the arc lines. It is also possible to differentiate between the lines of the first and second spark spectrum. Electrons in mercury vapour with velocities greater than the ionisation potential were confined into a beam by a magnetic field. The light produced was projected on the slit of a spectroscope with the direction of the beam at right angle to the slit. Perpendicular to the beam an electric field withdrew positive ions before they recombined. The intensity of the arc lines was found to be independent of the electric field which indicates that recombination contributes very little to the formation of these lines. Two sets of exposures of different spectral lines with and without across field were taken and compared. It is noticed that the arc lines and the lines of the first spark spectrum are unaffected by the field while the lines due to the doubly charged ions show a change in their intensity distribution.

Duffendack and Koppius (1939) examining the radiation from negative glow found that intensities of the family of transitions ending with $6^3 P$ states increased according to an exponential saturation curve with mercury concentration and increased linearly with tube current. Assuming in steady state of discharge, the intensity of a spectral line due to the transition from state j to state k of the atom will be proportional to the concentration N_j , of atoms in the

state j , the probability of transition jk and the magnitude of the light quantum $h\nu$ i.e

$$I_{\nu_j} \propto N_j A_{jk} h\nu$$

and in terms of the current i , passing through the discharge, it was written

$$I_{\nu_j} = A \cdot i \left(1 - e^{-pd/\lambda_{IE}} \right) \dots(1.20).$$

where "A" is a multiplicative constant, "p" is the pressure in mm. Hg. "d" is distance between electrodes and λ_{IE} = average mean free path for the excitation of mercury atom at unit pressure i.e.

$$1/\lambda_E = p/\lambda_{IE} \dots(1.21).$$

(0°C and 1 mm. Hg.) and when mercury and other foreign atom is present the formula was modified to

$$I_{\nu_j} = A \cdot i \frac{1/\lambda_E}{1/\lambda_E + 1/\lambda_A} \left(1 - e^{-pd/\lambda_m} \right) P_j \dots(1.22).$$

where λ_A is the average mean free path of an electron for excitation of a foreign atom. λ_m is the average mean free path of an electron for excitation of either a mercury or a foreign atom. At the densities studied no reversal whatsoever was observed. In mixtures of argon, in addition to the same saturation behaviour, excitation was found to be apportioned between mercury and argon in the proportions of their relative abundances. Everything observed was in complete accord with the hypothesis that monoenergetic primary electrons in a fixed finite numbers were expended in single collisions to the extent to which the abundance

of obstructing molecules permitted. Assuming monoenergetic stream of electrons having a particle current density i_e the number of losses from a unit area of the beam in a distance dx is

$$\frac{di}{e} = - \sigma \cdot \frac{i}{e} \cdot N_0 \cdot dx \quad \dots (1.23)$$

and is equal to the change of particle current density. Integrating

$$i = i_0 \cdot e^{-\sigma N_0 x} \quad \dots (1.24)$$

is the equation of decrement of the primary electron stream. The cross section is the cross section for all significant energy losses, ionisation plus excitation of all kinds. The power radiated per unit volume in any transition excited by the electron stream is now given by

$$f_{ji} \cdot h \nu_{ji} \cdot \sigma_j \cdot \frac{i}{e} \cdot N_0 \cdot e^{-\sigma N_0 x}$$

Integrated over the whole stream from cathode to anode the power radiated is

$$f_{ji} \cdot h \nu_{ji} \cdot \frac{\sigma_j}{\sigma} \cdot \frac{I_0}{e} \cdot \left(1 - e^{-\sigma N_0 x} \right)$$

where f measures transitions probability.

While the theoretical dependence conforms well with the experimental result, the total elatation cross section σ required by Duffendack and Koppine to fit their curves is surprisingly large. In the radiations stimulated by monoenergetic electrons, general opinion favours direct electron excitation as the chief mechanism of population rather than recombination.

The thermal electron discharges are positive columns of glows, arcs and sparks, high frequency discharges and anode glows. Analysis of the radiation from thermal discharges must be made on a basis of electron concentration and its velocity distribution. Discharges are never and can never be in true thermal equilibrium. Experiment shows and theory suggests that it is reasonably accurate

to consider the electron temperature, which governs the velocity distribution, constant over large regions of the discharge. This is because the electron temperature is almost directly proportional to the electrostatic field in the gas and the electrostatic field is tangentially constant at least from its conservative properties. Further more, in the absence of space charges which are usually small in regions where thermal elatation predominates, there can be no change in the normal component either thus establishing the conditions for constancy of electron temperature. A fairly general theory of this type can be based on an assumption of separability of space and velocity dependence of the electron distribution to give the number of primary electrons

dN_- at x, y, z having velocity u_x, u_y, u_z

as

$$dN_- = N_-(x, y, z) dx dy dz \phi(u_x, u_y, u_z) du_x du_y du_z$$

The production function can now be written for elatations of a type governed by the cross-section $\sigma_j(u)$ per unit volume per unit time,

$$P_j = 4\pi N_- \int_{u_{min}}^{\infty} u^3 \sigma_j \phi \cdot du \quad \text{where}$$

$$u = (u_x^2 + u_y^2 + u_z^2)^{1/2}$$

and electron velocity is assumed much larger than molecular velocity. Since the major portion of discharge current density is given by the expression $i = e N \cdot U$ for the electron current density, at least in gases which do not attach electrons, the production is directly proportional to current density, and if radiation is the chief energy loss mechanism, the radiation must be proportional to the current.

Much qualitative and some truly quantitative knowledge exist concerning the radiation from the glow discharge. A large part of this applies to the positive column which is by far the most spectacular region of the discharge. Angstrom found that the radiation reaching a heliometer from the positive column was only a few percent of the energy supplied to the column electrically probably because the tube walls failed to transmit the bulk of the radiation of the discharge. Penning (1938) has made an analysis of the energy losses by the thermal electrons swarm. He finds that when an electron current moves through a gas, the energy received from the electric field is partly lost in collisions with the gas molecules. An infinitely small electron current " i " flows in a homogenous electric field E which case occurs in the starting of a glow discharge between large parallel plates at not too high pressures. From the observations it is clear that only for very low values of E/p the energy transfer in elastic collisions is important which may be treated to a certain extent with the classical laws for mechanical collisions. At higher values of E/p however the conduction of electricity through the gas is governed wholly by the laws of quantised energy transfer between electrons, molecules and excited molecules .

Hodge and Michels (1928) examined the pressure dependence of radiations from positive column of helium discharge. The absolute and relative intensities of thirteen lines of the helium spectrum extending through the visible regions have been measured by a modification of the method developed by Orstein (1925) and Dorgelo (1925). The method consisted in comparing each line directly with the known emission from a tungsten filament, operated under constant conditions. The results for a discharge in a capillary tube, with pressures from 1.92 to 34.3 mm. Hg. show that the absolute intensities increase rapidly to a maximum for pressure in the neighbourhood of 2 to 34 mm, below which they tend toward zero. The relative intensities of the singlet system are favoured by lowered pressures, and the higher

members of the triplet system are likewise favoured over the lower members, while the relative intensities within the singlet series show little effect of pressure. Following observation of Dymond (1925) that the efficiency of excitation of a given initial state is greatest when the energy of the exciting electron is only slightly greater than that needed to excite that state, they obtained the probability relation from kinetic theory consideration as

$$e^{-v_1/gy} - e^{-v_2/gy}$$

where for a given state with energy v_1 will be excited in most cases by electrons which have, at the time of impact, an energy between that necessary for excitation of this state and that of the next higher state v_2 . "g" is the potential gradient in the tube and "y" is the electron mean free path. This relation though does not agree quantitatively yet gives the general type of curve obtained. The indications are that the two processes (1) dissociative recombination of molecular helium ions and (2) collisions of excited states with neutrals are active here also. The enhancement of the upper triplet states is understandable if process (3) is active, since the energy deficiency between corresponding singlet and triplet levels is less for the higher levels.

Parkinson (1951) observed interesting behaviour in a 15 Kc alternating current glow discharge in air and noble gases, and especially in helium, where the molecular ion seems to play an important role. Observing the light in front of one electrode which is alternately a cathode and an anode, Parkinson found that the neutral molecular band spectrum was strong during the anode period and absent during the cathode period. At the same time atomic radiations were observed which displayed the same after glow decay behaviour as the molecular bands during the anode cycle, but followed the discharge current wave form during the cathode cycle. Low level singlet transitions showed a preponderance of

cathode cycle current governed response over anode cycle after glow, but high level triplets have completely the reverse behaviour. Parkinson found that all decays occurred with the same time constant (35μ sec.). He found also that the intensity of the molecular and atomic after glows decreased very rapidly with pressure, as would be expected if the three body process of molecular ion formation were the contributory case. The light from the electrodes of an a.c. glow discharge in helium is found to be particularly rich in the He_2 spectrum. This light occurs at an unusual phase of the voltage cycle. The process which forms excited molecules also gives rise to excited atoms. Further more the process is inhibited by the presence of an electric field. There are indications that the process is one of recombination between electrons and atomic positive ions. It is a well known phenomenon that the light from near the anode of a d.c. glow discharge extends only as far as the front face of the anode being free of any luminosity. In an a.c. discharge the regions around the two electrodes appear the same to the eye. If investigated with a photomultiplier tube and oscilloscope it is found that the situation is really the same as in the d.c. case. The output of light is confined to the time during which the electrode is a cathode. There is no light output during the anode half cycle except from the positive column, which extends from a point a few mm. in front of the front face of the electrode along the tube to the other electrode. Further more the light from the electrode during the cathode half cycle is directly proportional to the current which itself is directly proportional to and in phase with the voltage. Thus if the current is a sine wave, the wave form of the light output is like the output of a half wave rectifier. This applies upto about 100 Kc. The above considerations have been found to be applied to discharges in air, neon, argon and krypton at all pressures and to helium below about 5 mm. The pressure dependence of molecular light and

molecular component of atomic light show an increase with pressure in the lower pressure region upto 35 mm. and 15 mm. after which for higher pressure the intensity decreases. But the normal component of atomic light intensity shows gradual increase as the pressure is lowered. The intensity of molecular light is governed by two independent factors. One is the presence of an electric field. The other factor causes an approximately exponential decrease in molecular light with a time constant of 35μ sec. This time constant is independent of pressure. It is evidently due to a decrease in the concentration of some participant in the process which forms molecules. It seems unlikely that this can represent the fall in the concentration of metastable atoms. The rate of decrease found here is reasonable for the concentration of positive atomic ions. The atomic spectrum of the negative glow during the anode half cycle is suggestive of a recombination spectrum. The different considerations point to a recombination process in which an excited molecule and an excited atom are formed.

Microwave and high frequency discharges have almost identical emission and temperature characteristics with steady glow discharges of the same power density. In a point to point comparison Beck (1935) found a steady glow discharge in mercury indistinguishable from 100 Mc/s discharge. Margenau and Hartmann (1948) have shown that the theory of microwave discharges leads to this same conclusion of similarity, barring the space charge effects which are possible in steady discharges. Corliss, Hoxman and Westfall (1953) find that an electrodeless discharge at 300 Mc/s will excite the pure metal spectrum of involatile metals which have been introduced as pure halides. The atomic spectra of high melting point metals can be excited in electrodeless lamps if a volatile salt of the metal is introduced into the lamp together with a noble gas at a pressure of a few mm. Hg. The lamps are simply prepared from lengths of pyrex or vycor tubing, excited with microwaves and produce sharp spectral lines free from self reversal. Lamps have been prepared which emit atomic spectra of Ba, Ti, Fe, Ni,

Cu, Mo and U. Relative intensities of copper line wavelength \AA 5153.24, 5218.20, 5105.54, 5782.13 and 5700.24 from d.c. arcs and a CuCl_2 lamp are measured. Frisch and Schreidern (1949) proposed a similar discharge mechanism for quantitative spectrographic analysis of gas mixtures.

Roklin (1939) observed the effect of a magnetic field on the radiation from a mercury vapour discharge where

$$p \sim 10^{-3} \text{ m. m. Hg} ; \quad i = 1.5 \text{ to } 4 \text{ Amp.}$$

He used two solenoids spaced a few cm. apart, the magnetic fields could be coincident, given an almost uniform field between them or opposite giving a distorted field having strong radial components. The image of a diameter section was observed in a spectroscope and the intensities of the 1850 \AA and 2537 \AA resonance lines were measured by the brightness of a fluorescent probe placed in the tube. With coincident fields the discharge is visibly constricted into a cord, at first rapidly and then more slowly with increasing H. At higher pressures or currents the effect is less marked and finally ceases to be noticeable. The cord follows the lines of magnetic force and can be moved about by displacing the solenoid coils or by the presence of a magnetic field. At the centre of the tube the variation of relative intensity of several lines like 5791 \AA , 3906 \AA shows first a maxima near $H = 100$ oersted and almost no change at higher magnetic field. The line 3704 \AA gradually decreases in relative intensity with magnetic field with almost no change for magnetic field of the order of 200 oersted. The fall in intensity is pronounced in lines from high excitation levels, indicating a decrease in number of fast electrons. The maximum is due to two opposing effects, the increased concentration of electrons at centre and the decrease in their energy. Roklin comes to the general conclusion that the constriction of the discharge is due to the radial components of the magnetic field on the cathode side of the plasma the longitudinal part of the field however, did not extend far enough for a proper assessment of its effect.

Experiments have been made on the effect of magnetic fields on the radiation from the column of a constricted discharge in a capillary tube in transverse magnetic field. Kulkarni (1944) studying discharges in He, Ne and N₂ found that the intensity of a spectrum line reaches a maximum and then decreases quickly with increasing magnetic field H. The value of H at the intensity maximum depends on the wavelength of the line and the presence of any foreign gas. For a given discharge voltage V there is a critical H above which the discharge goes out and just below which it throbs. In these conditions these gases show the molecular spectrum in regions near the electrodes. The applied potential for maintenance of discharge is of the order of 10 KV to 15 KV and H of the order of 10 Kilo oersted without any specification of pressure. In the Zeeman effect experiment usually performed in the laboratory with a neon tube, it is observed that the magnetic field, besides producing the well known splitting of the lines, effects to a marked extent the intensity of the glow in the discharge tube. It was thought that a detailed spectroscopic investigation of the effect of the magnetic field on the variation in the intensity distribution amongst the spectral lines, would give useful information about the collision processes involved in the mechanism of discharge of electricity in rarefied gases. Preliminary experiments with helium, neon and hydrogen have revealed some interesting facts. The experiments were performed with the ordinary capillary discharge tubes placed between the poles of an electromagnet capable of giving a field upto 10,000 Gauss. The tubes were worked between 10 and 15 K volts. The results of observations may be summarised as follows :- (1) The intensity of lines increases with the magnetic field, reaches a maximum and then decreases, the decrease being more rapid than the increase. This is shown in spectrum of helium with magnetic fields 4, 6.2 and 7.8 K Gauss. (2) The field at which a line reaches its maximum intensity, the conditions of pressure and excitation remaining the same, depends on two factors (a) wavelength and (b) the presence of foreign gas. The dependence

on wavelength was best exhibited with the Balmer series of hydrogen. " H_{δ} " appeared as a weak line in zero field, reached a maximum intensity at 4000 Gauss, after which the intensity fell rapidly and the line was not excited at all at higher field. " H_{γ} " reached its maximum intensity at 600 gauss, whereas H_{β} and H_{α} showed a continuous increase in intensity even upto 10000 Gauss, the maximum field obtainable in the experiment. The effect of foreign gas on the intensity of the lines is shown which gives the spectra of a mixture of helium and neon. The spectrum were obtained for magnetic fields of strength 4.9, 7 and 8.2 Kilo Gauss respectively. It is to be noted here that in contrast with the case of (1) the lines continuously increase in intensity without showing a maximum. The effect of the foreign neon gas seems to be to increase the field strength at which the helium lines will have their maximum intensity. (3) For a given applied potential at the terminals there is what may be called a "critical" field at which the discharge stops altogether and the tube becomes nonconducting. As this critical field is approached and just before what may be called the throbbing state of the tube, the intensity in the capillary portions which is kept in the magnetic field is considerably reduced and the intensity of the glow in the wider portions of the tube near the electrodes, is correspondingly increased. A spectrum of helium from this wider portions is shown under this condition without magnetic field and with 6.2K Gauss magnetic field. It is observed that without the field only weak atomic spectrum is produced, while with the field on, not only is the intensity of the atomic lines increased but the molecular spectrum of helium is fully brought out. The spectra from the wider portions of the tube for lower values of the field at the capillary, showed only the atomic lines. It is to be inferred that the excitation of the helium molecular bands is a sudden process occurring within a narrow range of the field strength near about the throbbing field. Most of the He molecular bands are identified with the triplet electronic states and they involve only

two lowest states

$$2p\pi^3\pi_g \quad \text{and} \quad 2s\sigma^3 \sum_u^+$$

Davies (1953) made measurements of the intensity distribution in the recombination spectrum, the relative densities of the electrons and their velocity distribution in the positive column of a cesium discharge as determined in the presence of a longitudinal magnetic field. The effect of a longitudinal magnetic field was investigated for both d.c. and r.f. discharges. In both cases, as the intensity of the magnetic field was increased, the glow surrounding each of the electrodes was compressed towards the electrode, but no visible effect was produced in the positive column. The spectrographic determination of the distribution of intensity in the recombination continuum showed that there was Maxwellian distribution of electron speeds in all discharges investigated, within the experimental error. An initial survey was carried out over the available range of discharge pressure, with the r.f. discharge current maintained at 0.98 Amp (r.m.s.). In this case the electron temperature T_e was evaluated using equation

$$\log [\nu \cdot J(\nu)] = - \frac{h\nu}{kT_e} + \text{constant.} \quad \dots(1.25).$$

where $J(\nu)$ is the intensity of the 6P recombination radiation of frequency ν . An additional experiment with r.f. excitation was carried out with a mean current density of $5A\text{ cm}^{-2}$ at a frequency of 6.65 Mc/s. At a pressure of 0.078 mm. Hg, the value of T_e was increased by $175 \pm 100.K$ by a magnetic field intensity $H = 1450$ Gauss, from its initial value of 4000.K for $H = 0$. The increase was determined using equations

$$N_{1a} / N_{1b} = \left[J_a(\nu) / J_b(\nu) \right]^{1/2} \left(T_{1a} / T_{1b} \right)^{3/4} \exp \left[h\nu (T_{1a}^{-1} - T_{1b}^{-1}) / 2k \right]$$

i.e

$$\frac{d}{d\nu} \left[\log \left\{ J_a(\nu) / J_b(\nu) \right\} \right] = - 2.084 \times 10^{-11} (T_{1a}^{-1} - T_{1b}^{-1})$$

where N_{1a} and N_{1b} are the number of electrons/c.c. in state "a" and "b"

respectively.

In all the experiments in which the discharge was excited by r.f. energy, the application of a longitudinal magnetic field produced no measurable change in the axial value of the electron density N_1 . It is estimated that a change in the value of N_1 of 5% or more would have been detected. Measurements were also made of the change produced in the value of the total potential drop across the discharge tube when it was subject to a longitudinal magnetic field. In all cases the change in potential difference across the tube was less than 3% for a value of the field $H = 1500$ Gauss. In general the potential difference was increased by a magnetic field of this value, but the increase was not always a monotonic function of H .

Hobbs, McWhirter, Griffin and Jones (1961) studied both experimentally and theoretically the temporal variation of the intensity of line radiation in the ultraviolet from impurities in the zeta discharge. The comparison between computed and observed intensities is discussed in terms of simple ionization recombination and excitation processes and used to establish the adequacy of the ionization coefficients employed. If the spectrum emitted by zeta discharge is examined it is found to contain lines of various impurity elements. Further examinations show that the line intensities vary in time during the period of the discharge in a grossly reproducible manner. The intensity variation of the impurity spectral lines from the impurities nitrogen, carbon, oxygen has been observed from the zeta discharge. The data was obtained using a grazing incidence vacuum monochromator with an effective wavelength range of 100 Å to 1500 Å. The line intensities were measured by a photomultiplier with a sodium salicylate phosphor and were recorded by photographing an oscilloscope trace.

Different authors utilised the absolute intensity of a line and relative intensity of a family of lines to measure the electron density, electron temperature etc. The absolute intensity I of a spectral line by a transition

from an upper state "S" to a lower state "t" is given by Pearce (1958)

$$I = \frac{g_s n e^{-E_s/KT} A_{st} h \nu_0}{U(\tau) \cdot 4\pi} \dots (1.26)$$

with suffixes "S" and "t" indicate the upper and lower states respectively and

g_s = statistical weight of the upper state

n = total number of atoms/c.c. of the element concerned

E_s = energy of the upper state in ergs

K = Boltzman's constant.

T = absolute temperature °K ; A_{st} = Einstein's transition probability from upper to lower level

h = Planck's constant; ν_0 = central frequency of the line

$U(\tau)$ = partition function of the atom.

Jahn (1961) utilised several method for determining the temperature of plasma jet derived from argon containig 5% hydrogen based on the absolute intensity of or H_β line, the relative intensity of H_α and H_β lines and the profile of H_β line. Intensity measurements were made photoelectrically.

Reeves and Parkinson (1961) also measured the peak brightness temperature and spectral energy distribution of flash discharges of Lyman co-axial and capillary types for the wavelength range from 2580 Å to 4520 Å by measuring the intensity of lines and utilising the derived emission coefficient for low radiation density for the frequency independent region as

$$\epsilon_\nu = \frac{32 \pi^2}{3\sqrt{3}} \cdot \frac{e^6}{c (2\pi m)^{3/2}} \cdot (\overline{Z+S})^2 \cdot \frac{N_e N_i}{(KT)^{1/2}} \dots (1.27)$$

and for frequency dependent region

$$\left(\right) = \frac{32 \pi^2}{3 \sqrt{3}} \frac{e^6}{c (2 \pi m)^{3/2}} (\bar{Z} + S)^2 \frac{N_e N_i}{(K T)^{1/2}} \frac{\epsilon^{h \nu_g / K T}}{\left(\epsilon^{h \nu / K T} - 1 \right)} \dots (1.28)$$

where N_e = electron concentration, e = electron charge, N_i = ion concentration, Z = atomic number and $\bar{Z} + S$ = effective atomic number in which

$$n^2 \frac{E_i - E_n}{E_{iH}} \left\langle (\bar{Z} + S) \right\rangle \left\langle Z \right\rangle$$

when E_i = ionisation energy n = principle quantum number, E_n = excitation energy E_{iH} = ionisation energy of hydrogen. Using Wien's law for the standard lamp and Planck's for the flash tube, the brightness temperature of the standard capillary discharge was obtained from the relationship

$$I_{SL} / I_{FL} = \left(\epsilon^{-c_2 / \lambda \cdot S} \left(\epsilon^{c_2 / \lambda \cdot S_{FL}} - 1 \right) \right) \dots (1.29)$$

when S = brightness temperature of the standard lamp, S_{FL} = brightness temperature of flash source, $c_2 = 1.438$ cm. deg., I_{FL} = recorded signal for flash source, I_{SL} = recorded signal for standard lamp.

Golant, Krivosheev and Tachnev (1956) investigated the plasma parameters for a stationary ultrahigh frequency discharge in argon and their dependence on magnetic field intensity. The U.H.F. is 3150 Mc/s. It is observed that the charged particle densities and total light intensities are maximum near the second and third harmonics of the electron cyclotron frequency i.e.

$$\omega = 2 \omega_H, \quad 3 \omega_H$$

No maxima are observed near the electron cyclotron resonance frequency. When the U.H.F. power input is approximately 10 watt/cm³, the magnetic field 500 oersteds and pressure of argon approximately 1×10^{-2} mm. Hg. densities in excess of 10^{12} cm.⁻³ are obtained.

Burlamacchi and Fratini (1966) reports the enhanced emission of the 3889 Å (3³P - 2²S) and 5016 Å (3¹P - 2¹S) lines of He during the initial transient of a pulsed r.f. discharge with oscillator frequency at 24 Mc/s. Very strong overshoots have been observed in the 3889 Å and 5016 Å lines when viewed along the axis of the tube, both in pure He and He-Ne mixture. The overshoots of the 3889 Å and 5016 Å lines have been interpreted as due to the low 2² metastable densities and hence low absorption of these lines during the initial transient. A measurement of the absorption present under pulsed conditions has been attempted for the 3889 Å and 5016 Å lines. The pressure dependence of the 5016 Å output is shown for both He and He-Ne. The full signal intensity is plotted. The optimum values of pressure for steady state and overshoot outputs results from a balance between the increasing atoms density on one side and the increasing loss mechanisms and the falling electron temperature on the other side. No substantial difference has been found between the case of pure gas and He-Ne mixture, though in the latter case the ratio between peak and steady state values is higher and the emission vanishes at higher pressure.

D. ELECTRICAL BREAKDOWN OF GASES IN CROSSED
ELECTRIC AND MAGNETIC FIELD.

SECONDARY EFFECTS IN CASE OF ELECTRODELESS DISCHARGE EXCITED BY A
TRANSFORMER.

The secondary effects in a d.c. discharge with electrodes made of different elements have been studied quite extensively by Townsend and many others from as early as 1904. The mechanism of discharge excited by a transformer is however substantially the same as that of a d.c. discharge. Townsend (1902) in his ionisation theory derived an expression for the ionisation current flowing in a gap (d) when the cathode is irradiated as

$$i/i_0 = e^{\alpha d} \quad (1.30)$$

where i_0 = initial current, α = number of ion pairs produced per unit length per primary electron. It suggests that the plot of $\ln(i/i_0)$ against d would be a straight line. But it was found that the curve bent upwards terminating abruptly to a value producing a spark. This indicates that another source of ionisation has arisen other than ionisation by electron collision. Townsend's obvious choice was ionisation by positive ions and he deduced a relation of the form

$$\frac{i}{i_0} = \frac{e^{\alpha d}}{1 - \beta/d \cdot e^{\alpha d}} \quad (1.31)$$

where β = ionisation coefficient due to positive ions.

The positive ion theory was criticised by Thomson (1912), Bohr (1913) and others. The mechanism was however studied by many workers; Sutton & Muzon (1930, 1931), Muzon (1932), Beck (1930, 1934), Nordmeyer (1933), Varney (1935, 1936, 1938), Rostagni (1934). These results have been discussed by Loeb (1947). However Fetz and Medicus (1948) has given strong support to the mechanism as a possible process of ionisation.

POSITIVE ION BOMBARDMENT AT THE CATHODE.

Another mechanism of emission of secondary electrons proposed by Townsend and also by Holst and Oosterhuis (1922) was the emission of electrons by bombardment of positive ions of the cathode. A similar relation of the form,

$$i/i_0 = \frac{e^{\alpha d}}{1 - \gamma_p (e^{\alpha d} - 1)} \quad \text{which reduces to}$$

$$i/i_0 = \frac{e^{\alpha d}}{1 - \gamma_p e^{\alpha d}} \quad \text{for } e^{\alpha d} \gg 1 \quad (1.32)$$

has been deduced where γ_p = secondary ionisation coefficient due to positive ion bombardment at the cathode.

In this context we should clearly distinguish between the primary process and the secondary effect. When a field is applied electrons already present in the gas are accelerated and cause ionisation and only after ion pairs are formed in this manner do the +ve ions exist in the gap to cause ionisation or secondary emission from the cathode. When the source of charged particle is dependent on another source or excitation within the discharge it is termed as secondary effect. Only if the external energy (electrons from external source) could cause ionisation it is the case of primary ionisation process.

PHOTOIONIC PROCESS AT THE CATHODE; PHOTO IONISATION IN THE GAS

R.E. Brode and L.J. Neuman (1928) showed that in case of electron liberation by photons in the gas or at the cathode one could arrive at the questions closely similar to original Townsend's equation (1.31) by making certain simplifying assumptions. Hence photons may be considered as the agent for secondary emission of electrons. Direct measurement of photon production in Townsend discharge has

been made by Geballe (1944); Costa (1940) showed that radiation from a Townsend discharge produces photoelectric effects on subsidiary silver cathode. The action of photons to produce volume ionisation was recognised by Kenty (1933), Gravath (1935), Dechene (1936), Grainger (1933), Loeb (1947) and Raether (1938). A detailed discussion of the process of photo-ionisation has been given by Dutton (1953). Following simplified derivation of Little (1956) it can be shown that if α , the first Townsend coefficient be greater than the absorption coefficient, similar form of equation (1.32) can be arrived at. The up-curving of $\ln(i/i_0)$ versus d can be explained thus provided the absorption coefficient for photon is not too large. On the other hand sufficient absorption must be there to make secondary process important.

FIELD EMISSION .

If field emission in a Townsend discharge is to be a secondary effect it must be due to a surface layer of positive ions which covers the cathode. From Fowler & Nordheim's work (1928) it is known that the current density due to an applied field X at a metal surface is

$$j = 6.2 \times 10^{-6} (\mu/\phi)^{1/2} (\mu + \phi) X^2 \exp\left(-6.8 \times 10^7 \phi^{3/2}/X\right) \dots (1.33)$$

If however the surface is covered with a film of ions the potential barrier is not of the same type as considered by Fowler and Nordheim (The analysis is given by Stern, Gosling and Fowler, 1929 and is quoted by Hlewellyn Jones and Morgan, 1953 to explain some observations with aluminium cathodes). If the field intensification due to surface charge is considered, this is equivalent to emission from a metal of work function ϕ_1 covered with a thin layer of thickness d of another metal whose work function is ϕ_2 a potential gradient $(\phi_1 - \phi_2)/d$ is set up and equation (1.33) is modified. It is to be noted that field must not be very large but extended over

sufficient distance to make potential drop outside the barrier comparable with work function ϕ . In the steady state however the surface layer is continually bombarded by positive ions and the field will rise until film breakdown. This may imply that the film is constantly being punctured and reformed over the whole surface. If however there is a film we have in a steady discharge an emission process described by coefficient γ_p (emission due to bombardment at the cathode). The increased current flowing from the cathode would be formally included by increasing γ_p though the electrons would not appear at the same time as the electrons are extracted by the ions individually.

THERMIONIC EMISSION.

A simple arrangement may be used to include the effect of thermionic emission from the cathode but this is not possible with very small current density in a Townsend discharge. For the same reason thermal ionisation in volume need not be considered.

X-RAYS.

The emission of positive ions from the anode (Trump and Vander Graff, 1947) at a very high voltage and low pressure indicates that X-rays are certainly present and have to be taken into account for the consideration of secondary emission. It can be shown that similar type of equation as that which takes account of photon effect can be arrived at (Little, 1956).

FAST NEUTRAL ATOMS.

The action of fast neutral atom at the cathode is also to be considered as an acceptable secondary process as they are formed from ions by charge exchange collision. Once formed, an atom cannot gain further energy from the field as an

ion does. We assume it moves in the field direction and does not loose much energy at a collision. The derivation considering only the effect of positive ion is to be modified (Little, 1956) and we can arrive at the equation

$$\frac{i}{i_0} = \frac{e^{\alpha d}}{1 - G e^{\alpha d}}$$

... (1.34).

Where $G = \gamma_p (K-1) + \gamma_n K$

Where $K =$ fraction of ions which suffer charge exchange collision

$\gamma_n =$ contribution due to fast neutral atom.

Considering now the fast neutral atoms for volume ionisation we should note that in the inelastic scattering leading to ionisation which concern us here ions and atoms need not be treated differently. Theory indicates (Massey & Burhop, 1952) that curves of ionisation energy as a function of energy will be roughly the same for ions and atoms moving in their own gas. The original Townsend equation then follows immediately.

METASTABLE ATOMS.

No complete analysis of the action of metastable atoms appears to be available. There is also uncertainty in the rate of production of metastables in the discharge. However Dorrestein (1942) has used the secondary emission due to metastable atoms of He and Ne to measure the excitation function for the metastable states. Considering the action of metastable atoms, if a gas mixture is used, atoms of one gas may be ionised by metastable atoms of the other if $v_{i_1} \leq v_{m_2}$ with appropriate notation. This secondary mechanism may lead always to an increased current that can be expressed as an increase in α . Its effect on the curve of $\log (i/i_0)$ against d at constant X/p is to increase slope and not to introduce curvature at large d . However, although the phenomena is a secondary process the

secondary electrons are produced very near the place of origin of metastable atoms so that the process need not be considered as different from electrons directly produced by electron impact (Little, 1956).

Emission of secondary electrons due to striking of a primary electron on the surface of glass at a very low pressure has been considered by (Gill and Von Engel, 1948). The phenomena can be dealt with according to mechanism of +ve ion bombardment and we can reach an equation similar to equation (1.31).

Considering then all these mechanisms for the production of secondary electrons we can list them as

- 1) Ionisation due to +ve ion
- 2) Emission of electron due to bombardment of +ve ion on the cathode.
- 3) Ionisation due to photon and X-rays
- 4) Photoelectric effect at the cathode
- 5) Ionisation due to neutral atom
- 6) Field emission
- 7) Ionisation due to metastable atom
- 8) Thermionic emission
- 9) Emission of electron by the striking of primary electron on the glass surface at a very low pressure.

Considering the relative importance of the effects listed we can neglect the effect of neutral atoms as they have low energy. Field emission has never been shown to act in the discharges. Thermionic and thermal ionisation would not be anticipated in this low current discharge (Lohft and Raether, 1955). It can be shown that with the exception of metastable atom, all the effects are formally indistinguishable and if the constants are chosen correctly and absorption in the gas be small then

$$\frac{i}{i_0} = \frac{e^{\alpha d}}{1 - \gamma e^{\alpha d}}$$

provided $e^{\alpha d} \gg 1$

where γ is the generalised secondary ionisation co-efficient depending on all possible mechanism.

EXPERIMENTAL DETERMINATION OF FIRST AND SECOND TOWNSEND COEFFICIENT.

The first measurement of ionisation co-efficients in air, O_2 and H_2 by Townsend, (1902, 1904) and his school were extended to include N_2 by Hurst (1906). Hill and Bidderek, (1909, 1912) carried over measurements in argon and He. In all these studies both α and γ were measured over a limited range of E/p . Townsend's theories of sparking and ionisation were thus tested. Later Townsend and his group realised the importance of the presence of impurity in the gases for such measurements. Ayers, (1923) therefore undertook a redetermination of the coefficients in distinctly purer samples of H_2 , N_2 and argon. The results of Ayers did not agree with that of others of lower values of E/p , but in the upper range agreed fairly well with those of earlier workers except where the impurity was to be seriously questioned. The data of (Posin, 1936) in N_2 did not agree with that of Ayers, although he had purer sample. Hale, (1938) carried out experiments to obtain the values of α and γ over the range of E/p varying from 30 volt/cm. mm. of Hg. to 917 volts/cm. mm. of Hg. The work of (Bowls and Hale, (1938) as well as that of Penning and Kraithoff, 1936, 1937) have shown striking influence of impurities in the pure samples. (Crompton, Dutton and Haydon, (1953) have measured γ for a range of E/p from 20 to 25 volts/cm. mm. of Hg. The method of measurement was by measuring the pre-breakdown current and plotting $\ln(i/i_0)$ against d . The other methods of measuring γ were from (1) energy balance at the cathode proposed by A. Guntherschulze, W. Bar and A. Winter, (1938) and (2) by measuring the breakdown potential & using $V_s = f(pd)$ and $\gamma(e^{\alpha d} - 1) = 1$.

This method will be discussed in detail in the subsequent chapter. The determination of γ from the knowledge of breakdown of voltage and curves of α/p as a function of E/p have also been done by many workers (Drayvesteyn and Penning 1936, Schofer 1938, Engstrom 1938, Hale and Huxford 1947 ; all in rare gases and Badareu and Bratescu 1942) in Hg. vapours.

Studies of Drayvesteyn and Penning, (1936) pointed out that at high values of E/p , γ should have the same value as in vacuum but that it should decrease gradually with decreasing E/p , as a consequence of the increased loss of electrons by diffusion back at the cathode. At lower values of E/p , γ increases again and this has been attributed by Kruitheff and Penning, (1938) to liberation of electrons from cathode by photons or by metastable atoms. The importance of photons in causing the emission of electrons from cathode in discharges in the rare gases has also been studied by Kenty, (1933). Studies of relative influence of +ve ions and of metastables in a discharge in argon with activated vacuum cathodes have been made by (Huxford, 1939) and later by (Engstrom and Huxford, 1940). Their view was that the separation of various factors governing secondary processes is not readily achieved by study of static discharges, and they have proposed a new approach to the problem by study of the time lags in transient discharge; their analysis has been extended by (Newton, 1948). The influence of photon has been studied by (Costa, (1934, 1940), Schadi, (1938) and Hale (1938, 1939).). Dewelllyn Jones, (1939) has concluded that except for relatively low values of E/p in hydrogen, photon can not cause secondary emission from the cathode. Low values of γ in oxygen (Cragge and Keek, 1948) and for water drops in air (English, 1948) have been measured. The only direct measurement of γ in Hg. vapour appears to be those of (Badareu and Bratescu, (1944)). γ is found to be very much smaller than

its values in rare gases. Information in poly-atomic gases such as vapours like benzene, cyclohexane, toluene was obtained by Valerin and Petreson, (1943); γ is very small for $(E/p) < 400$ volt/cm. mm. of Hg. for all the three. This may be due to the fact that large molecular ions tend to dissociate when neutralised at the cathode, rather than release electrons from the metal surface.

Experiments have been made by Hanbeck (1951) and Molnar (1951) has analysed processes as caused by bombardment of cathode by positive, ^{ion} metastable atoms, and photons. Discharges in argon with several cathode materials have been studied. A Townsend discharge has been stimulated by photo-electrons generated by a shuttered light beam which illuminates the cathode of a gas filled tube. The transient character of the resultant current is observed. γ is defined as the number of electrons which are liberated at the cathode and enter the discharge stream per ion formed in the gas. It is then possible to write.

$$\gamma = f_{esc} \left(\gamma_i + \frac{d_r}{d_i} f_{rK} \gamma_r + \frac{d_m}{d_i} [\gamma_m f_{mK} + f_{m\gamma} f'_{rK} \gamma_r] \right)$$

where γ_i , γ_r and γ_m are contributions due to ion, photon and metastable atoms d_i , d_r , d_m are number of ions, photons and metastable atoms produced per ion per electron f_{esc} = fraction that escape back diffusion effect f_{rK} , f_{mK} = fraction of photons and metastables generated in the gas which reach the cathode, $f_{m\gamma}$ = fraction of metastables generated in the gas which are converted into radiating atom, f'_{rK} = fraction of photons from these radiating atoms that reach the cathode. In Hanbeck and Molnar's measurement the current is found to consist of a component in step with the stimulating light pulse and a component which lags by a time of about 1 m. second. The fast component is assumed to be described by a Townsend equation with γ coefficient given by

$$\gamma_f = f_{esc} \left[\gamma_i + \frac{d_r}{d_i} f_{rK} \gamma_r \right]$$

The total current is described by a Townsend equation with

$$\gamma = \gamma_f + \gamma_s$$

Where

$$\gamma_s = f_{esc} \frac{\alpha_m}{\alpha_i} \left[f_{mk} \gamma_m + f_{mk} f'_{rk} \gamma \right]$$

The values of γ_i , γ_m & γ_r are not considered to be better than 10 or 20%. γ_r is found to be much smaller than γ_m and γ_i which are closely equal.

The influence of oxide layer on the cathode has been discussed by Elwelllyn Jones and Parker, (1952). Investigation of Dutton et al (1952) gives improved stability and accuracy of measurements.

Experiments have confirmed the dependence of γ of E/p . The mathematical formulation of the variation of γ with E/p has been provided by Davis, Dutton and Elwelllyn Jones (1953), they have deduced a formula

$$\gamma = \frac{1}{1 + \frac{u}{\{(6\pi)^{1/2} w\}^{d-\mu}}} \cdot \frac{K g \theta}{d-\mu} \cdot \frac{\exp\left\{\frac{Pd(\alpha-\mu)}{P}\right\} - 1}{\exp\left\{\frac{Pd\alpha}{P}\right\} - 1} \dots (1.36).$$

where P = pressure, α = electrode separation, μ = mean absorption co-efficient for photons in the gas, θ = average number of photons produced by one electron moving 1 cm. in the field direction, K = the photo electric efficiency at the cathode, g = geometrical factor, u = most probable velocity with which electrons leave the cathode, w = drift velocity. But this theory has been worked out assuming that the only secondary effect is the photo-electric action at the cathode at high pressure.

They have not considered the various mechanisms which will contribute to the value of γ at different values of E/p . Although attempts have been made to account for the contribution of different secondary processes from time

lag study, the dependence of γ on E/p has not been considered from theoretical stand point. Sen & Ghosh, (1962) has studied the variation of γ in an electrodeless discharge in air with discharge tubes of different lengths within the pressure range from few microns to 1000μ . They found that γ varies with pressure and also with E/p as in the case of d.c. discharge. They derived a mathematical expression for the variation of γ with E/p ; this agrees well with the experimental results.

EFFECT OF MAGNETIC FIELD ON TOWNSEND'S SECOND COEFFICIENTS.

That Townsend's second co-efficient should vary with magnetic field has been expected by E Levin and Haydon (1958) to explain the dependence of breakdown voltage on magnetic field, but no adequate study has been done in this problem either from theoretical or experimental point of view. Some theoretical approach has been made however by (E Levin and Haydon, (1958) using the generalised coefficients.

$$\frac{\omega}{\alpha} = K (\gamma' + \delta/\alpha)$$

... (1.37).

where only the contribution of positive ion and photon at the cathode has been considered. Here ω/α = the generalised secondary ionisation co-efficient γ' = contribution due to +ve ion and δ/α due to photon at cathode, K = fraction of secondary electrons which remain free in the gas. They have obtained a relation of the form

$$\left(\frac{\omega}{\alpha}\right)_{0, E/P} - \left(\frac{\omega}{\alpha}\right)_{H/P, E/P} = K \left[\left(\frac{\delta}{\alpha}\right)_{0, E/P} - \left(\frac{\delta}{\alpha}\right)_{0, E/P'} \right]$$

... (1.38).

where $P' = \sqrt{1 + C_1 H^2 / P^2}$

e and m being electronic charge and mass, u the velocity of electron and L the mean free path at 1 mm. of Hg.

(Sen and Ghosh, (1962) have studied the variation of γ in crossed electric and magnetic field. From the measurement of breakdown potential in an electrodeless discharge in a magnetic field the values of γ_H , Townsend's second coefficient in a magnetic field, have been calculated and the curve between γ_H and H has been found to be hyperbolic in nature. Assuming an expression previously derived (Sen and Ghosh, 1962)

$$\gamma = A' E/P + \frac{B'}{E} + C' \quad (1.39)$$

they have deduced an expression for the variation of γ_H with magnetic field in an electrodeless discharge. The formula thus deduced can explain the observed variation of γ_H with magnetic field and the quantitative agreement is also satisfactory specially for low values of magnetic field.

ELECTRICAL BREAKDOWN OF GASES IN CROSSED ELECTRIC AND MAGNETIC FIELD.

The elucidation of the mechanism of electrical breakdown of gases in uniform fields is of intrinsic and technological importance and has aroused considerable interest over a number of years. The essence of the problem is the explanation why at a certain critical potential called the breakdown or sparking potential the gases cease to behave like insulators and become conductors of electricity and large current can develop if the circuit condition favours. Although attempts have been made by J.J. Thomson, Stark and other to explain the mechanism, first fruitful attempt was made by Townsend. He derived the relation between ionisation co-efficients defined as the number of ion-pairs produced when an electron (or ion)

has moved through unit length in the direction of the field and the electrons, which are the sole producers of ionisation have collided a great number of times with gas molecules. Excluding for the present, the effect of walls and electrodes Townsend deduced a relation for 1st Townsend's co-efficient.

$$\alpha / P = A e^{-BP/E}$$

where P is the pressure and E the applied field. Although the validity of this expression has been questioned by many authors (Loeb, 1947) and some of them have deduced expressions for α/P the results obtained from their expressions do not give any better results than Townsend's over an extended range (Sen and Ghosh, 1962). Later Von Engel has shown that provided suitable values are assigned to constant A & B, the validity of this expression can be extended for a wide range of E/P values (Von Engel, 1955). Later on the same expression has been deduced by (Kihara, (1952) from generalised assumptions.

We have seen previously that current flowing in a uniform field can be expressed by the relation

$$i = i_0 \frac{e^{\alpha d}}{1 - \gamma (e^{\alpha d} - 1)}$$

The value of $\gamma (e^{\alpha d} - 1)$ is zero at low voltage gradient but increases as voltage gradient is raised until

$$\gamma (e^{\alpha d} - 1) = 1 \tag{1.40}$$

Then i becomes infinite or indeterminate. According to the theory proposed by Townsend regarding spark breakdown this condition defines the onset of spark. The significance of this sparking condition has been discussed by various authors.

following a modified expression of (Holst and Oosterheris, 1923). The subject has been treated by (Loeb, 1947) in detail.

Thus Townsend's expression

$$\alpha / P = A e^{-BP/E}$$

...(1.41).

and $\gamma (e^{\alpha d} - 1) = 1$ permit us to give a value for the breakdown voltage, which has been deduced as

$$V_S = \frac{BPd}{C + \log Pd}$$

...(1.42)

where

$$C = \log \frac{A}{\log(1 + \gamma^{-1})}$$

...(1.43).

The expression shows a minimum for V_S , when $V_S = BPd$ assuming to be constant. The dependence of V_S on (Pd) was first established experimentally by de La Rue and Muller, (1880). Later Paschen concluded from extensive studies that V_S is a function of (Pd) only. This result is known as Paschen's law.

The breakdown between parallel plates has been investigated by (Townsend and Woolium, 1923, Penning 1931, Penning & Adink, (1934). In general the variation of V_S with (Pd) shows a minimum.

The influence of small quantity of other gas as impurity has been studied by (McCallum and Kalyaow, (1951). Influence of electrode has been studied by (Hewellyn Jones and Henderson, (1939) for six different cathode materials. Breakdown measurements in hydrogen have been studied by (Ehrenkranz (1939) and Fricke (1933) and Hg. vapour has been studied by (Hewellyn Jones and Galloway, (1939) and

(Grigorovici, (1939)). All the previous workers have used internal electrodes to determine the breakdown voltage, which has got a very marked influence on the breakdown voltage.

It has however been shown that if electrodeless discharge is maintained by a transformer (at 50 c/s) the mechanism of breakdown remains substantially the same as that of d.c. but the effect of electrode can be eliminated by this method and in our investigation we have adopted this method of excitation of discharge.

The breakdown of a gas in crossed electric and magnetic field has been the subject of investigation of many workers. (Meyer (1919, 1921)) studied the breakdown potential in air in presence of transverse magnetic field with discharge tubes of length 29.79 cm. within pressure range 1 mm. to 24 mm. of Hg. and magnetic field between 0 and 1885 gauss. He observed a rise in the sparking voltage for all values of pressure in presence of magnetic field. (Penning (1936)) studied the electrical discharge between to co-axial cylinders in an axial magnetic field at low pressure and found that with strong field there is a decrease in starting potential. (Wehrli, (1922)) made calculations ^{with} regard to the effect of magnetic field on breakdown condition of a gas by calculating the value of α , the first Townsend's co-efficient in a magnetic field He showed that under the influence of magnetic field the electrons describe a cycloidal path and the mean free path λ with change to λ_e so that

$$\lambda_e = \lambda \left[1 - \frac{e H^2 \lambda}{8 \times 10^8 E_m} \right]$$

... (1.44).

where H = magnetic field in gauss

E = Electric field

e/m = ratio of charge by mas of electron

Hence the effect is to increase the pressure to an equivalent pressure

$$P_e = \frac{P}{1 - \frac{eH^2\lambda}{8 \times 10^8 E_m}}$$

1-45

Using this expression Valle, (1950) found that breakdown potential in presence of magnetic field, considering γ to be constant is given by

$$V_{SH} = \frac{BPd / \left[1 - \frac{eH^2\lambda}{8 \times 10^8 E_m} \right]}{C + \log \frac{Pd}{1 - eH^2\lambda / 8 \times 10^8 E_m}}$$

... (1-46).

(Somerville, (1952) has given a critical discussion of Valle's theory and derived a new expression for V_{SH} without introducing the equivalent pressure concept. The derivation was based on the assumption of completely inelastic collision and an ionisation probability of unity for all those collisions for which the electron energy is greater than the ionisation energy of the gas molecules, d/P as deduced by Somerville is given by

$$= \frac{A \sinh \left[\frac{a}{2\lambda} \sqrt{1 - \frac{4BL}{Ea}} \right]}{\phi(\lambda/a) \sinh(a/2\lambda)}$$

... (1-47).

where $a = 8 \times 10^8 E_m / eH^2$.

$$\text{and } \phi(\lambda/a) = \coth \frac{a}{2\lambda} - \frac{2\lambda}{a}$$

A new approach to the problem was made by Blevin and Haydon, (1958) who considered the bulk properties of electron avalanches and hence calculated the electron mass energy, the drift velocity and other allied properties in the magnetic field. They deduced an expression for d/p as

$$\left(\frac{d}{p} \right)_{H/p, E/p} = A \left[1 + c_1 H^2/p^2 \right]^{1/2} \exp \left[\frac{-BP}{E} \sqrt{1 + c_1 H^2/p^2} \right]$$

...(1.48).

and the modified pressure as

$$\text{where } c_1 = \left[\frac{e}{m} \frac{L}{u} \right]^2$$

where u = velocity of electron and L = mean free path of electrons in the gas at 1 mm. pressure. The two expressions for equivalent pressure given by (Wehrli and Blevin and Haydon, 1958) are different from one another and their range of validity has been discussed by Sen and Ghosh, (1962) over a range of pressure between 1μ to 1000μ . The work so far done cannot explain all the experimental results regarding the effect of magnetic field on the breakdown voltage. Consequently this aspect of the discharge phenomena has also been studied in the present investigation.

RADIOFREQUENCY BREAKDOWN OF GASES.

(a) Without magnetic field (b) With magnetic field.

The mechanism of the breakdown of gases for an alternating voltage at 50 cycles/sec is substantially the same as that for d.c. voltage. However, under the influence of a high frequency alternating field, free electrons in a gas may acquire energies sufficient to excite and to ionise the neutral gas molecules. When the field is sufficiently large, the ionisation process is cumulative and the gas breaks down into a luminous glow discharge. The exciting field may be applied directly by electrodes connected to the source of high frequency potential. Alternatively the gas may be excited by a h.f. current flowing in a nearby conductor. The first type of discharge is called E - discharge and second type H - discharge. The mechanism of E and H discharges are fundamentally the same and division into two types is justified only when the wavelength of the exciting voltage is large compared with the linear dimension of the discharge tube. Comparatively little study has been made of H- discharge. The reason is probably to be found in the difficulties experienced in making precise measurements as the path of the discharge current is closed and there are no electrodes between which current and p.d. may be measured. The breakdown mechanism in E- discharge and the magnitude of the breakdown voltage V_b of a gaseous discharge in an a.c. field depend upon the nature and the pressure of the gas, the frequency of the applied field and the linear dimension of the discharge tube. The general characteristics of the breakdown curves have been studied by many workers and it has been reviewed by Darrow (1932,1933). One of the earliest workers, Thomson (1930,1934) enunciated two conditions for breakdown

in a high frequency field. Assuming the electron under the influence of an a.c. field, the first criterion was that in time "t" the electron must acquire sufficient energy from the field so that the energy is either equal or greater than the ionisation energy of the gas; consequently the first condition states that

$$\frac{1}{2} m \left[\frac{E}{\omega} \cdot \frac{e}{m} \sin \omega t \right]^2 \geq e V_i \quad (1.49)$$

where V_i = ionisation

potential of the gas. The second condition was that the distance traversed by the electron in time "t" must be either equal to or smaller than the mean free path for the electron in the gas.

Hence

$$\frac{E}{\omega^2} \cdot \frac{e}{m} (1 - \cos \omega t) \leq \lambda_e \quad (1.50)$$

Combining these two conditions he obtained an equation for the breakdown voltage which is a function of pressure and frequency and shows that at a certain pressure the breakdown voltage becomes a minimum. Thomson (1937) next studied the starting potential for hydrogen within the pressure range (0.25 mm. to 9.5 mm.) and for frequency 1.8 Mc/s to 99 Mc/s. In case of lower frequency (below 2.63 Mc/s) he obtained double minima and above this frequency single minimum. Double minima was also observed by Guttons (1928) who concluded that these were due to resonance phenomena in the gas; Gill and Donaldson (1931) found that the double minima disappeared if the discharges were away from the walls of the tube. To explain this, Thomson (1937) attempted to modify his theory. In order that a typical electron may acquire the maximum energy at a time, it is assumed that the electron begins to move at a time $t=0$ when the electric field is $E \cos(-\phi)$. Then the ionising velocity will be most quickly attained if it is acquired in a time t_1 such that the electric field at time t_1 is $E \cos(\phi)$, for under this condition

$$\int_0^{t_1} \cos(2\pi ft - \phi) dt$$

is a maximum.

Gill and Donaldson (1931) showed that when the excitation was by a field at right angles to the long axis of the tube, double minima appear and when the field was along the axis one minimum (that at higher pressure) disappeared.

The explanation is seen by considering a cloud of electrons oscillating in the gas under the influence of the field. At a fixed pressure, as the field is increased the rate of ionisation increases and when this is just greater than the rate of loss, due mainly to diffusion, the glow appears. Now if the pressure is reduced the electrons acquire more energy from the field owing to their increased free path and the critical force required for breakdown is less. However as the pressure is reduced the amplitude of oscillation of the electron also increases and when this becomes of the same order as the distance apart of the walls, rate of loss of electrons increases rapidly and the breakdown voltage is increased.

The calculations of Gill and Donaldson relating to their conditions of experiments are in agreement with their views.

Breakdown in hydrogen for frequencies 5 to 11 Mc/s for $p_{gd} = 0.2$ to 30 mm. cm. of Hg. was studied by Githens (1940) who attempted to correlate the appearance of the minima of (V_g, p_{gd}) curves with the position of the walls of the discharge tube relative to the electrodes. He concluded that the breakdown of the h.f. discharge occurred through three different processes which he denoted by modes, a, b, c, each of which gave rise to a minimum in (V_g, p_{gd}) curve. Similar results were observed by Fin (1943, 1949) using small gaps in air at pressures from 59 mm. to 764 mm for frequencies ranging from 100 Mc/s to 300 Mc/s.

Hale (1948) tried to explain his measurements in argon and xenon over the range of frequencies 5 Mc/s to 50 Mc/s and at gas pressure 20-50 microns by

assuming that the breakdown potential for h.f. field is determined by those electrons in the gas which succeed in acquiring ionising energy in one mean free path; there is considerable divergence of the theoretically calculated breakdown voltage with experimental results in case of lower frequencies. The value of the mean free path of the electron used was that given by Kinetic theory which can hardly be correct. As is known, the mean free path of the electron varies with the energy of the electron and as the energy of the electron varies between zero and ionising energy, what is needed is an effective mean free path. Also the assumption that the probability of ionisation becomes a maximum when the electron acquires the ionising energy is not supported by experimental results because it has been shown by Smith (1930) that efficiency of ionisation increases quite rapidly with increasing electron energies slightly above the ionising energy.

The extent of the influence of the discharge in the walls and electrodes upon breakdown mechanism depends upon the relative magnitudes of p, f and d where p is the pressure f is the frequency and d is the electrode separation. Dlawellyn Jones and Morgan (1951) showed that when " f " and " p " are sufficiently high the amplitude of motion of the electron cloud is small, and it can be much less than the linear dimensions of the discharge tube; V_g is independent of the nature of electrode surface and secondary electron production at the electrode surfaces does not appear to play ^a important part. However at very low pressure, experiments of Gill and Von Engel (1948, 1949) and also those of Chenot (1948) show that a discharge can be started, provided the frequency is greater than a critical value, at quite a low potential which is independent of the pressure of the gas. In this case Gill and Von Engel have assumed that a single electron strikes the opposite glass surface and release the secondary electrons which move in phase with the applied electric field and release further electrons from the walls.

Applicability of similarity principle in h.f. discharge has been studied by Mewell Jones (1951, 1953) and his co-workers. Townsend and Williams (1958) studied the breakdown condition in air and hydrogen using a pair of geometrically similar electrode system and measurements were made for values of $p \cdot d = 15$ mm. cm. of Hg. and frequency 5 Mc/sec. to 70 Mc/sec. for $f = 10$ Mc/s or more, double minima appeared. The first minimum was not very sensitive to change of frequency but the second minimum moved to higher values of V_g and "P" as the frequency is decreased. The similarity theorem was found to be obeyed within the frequency range investigated. They have concluded that the multiple minima in ($V_g, p \cdot d$) curves at high frequency can be interpreted on the basis of a single breakdown mechanism involving electron generation by collision with gas molecule and loss by diffusion and drift to the electrodes and to the walls of the discharge tube.

The first published results for breakdown in ultrahigh frequency region, appear to be those of Cooper (1947) who made measurements of the breakdown in air, in co-axial lines and wave guides for gaps between 0.1 and 0.3 cm. at gas pressure 20-760 mm. At the two wavelengths (10.7 cm. and 3.1 cm.) and the breakdown gradient was found to be 70% of the d.c. breakdown value. Similar measurements were made by Posin (1948) who found that for 3 cm. wave, breakdown voltage for a 0.043 cm. gap in air under atmospheric condition is substantially independent of pulse duration provided that duration exceeds 4 secs. The nature of spark mechanism in a cavity resonator at these wavelengths has been studied by Prowse and Cooper (1948) and by Prowse and Jasinski (1949) using photographic and spectroscopic methods.

Series of investigations on microwave breakdown in gases in cylindrical cavities and between co-axial cylinders at a wavelength of 9.6 cm. have been made by S.C. Brown and his colleagues (1948, 1949, 1959, 1956). The gaps studied range from 0.06 to 7.6 cm. in air at pressure from 0.1 to 100 mm. Hg. The results are discussed in terms of a

new theory for ultra high frequency breakdown, which is based on the criterion that at the point of breakdown ionisation rate equals the rate of loss due to diffusion. Other processes of removal of electrons, such as attachment and recombination, are considered to be negligible for the type of the discharges studied; when the gap length is small compared with the wavelength, the electronic i.e. mean free path and the amplitude of oscillation, the breakdown condition is obtained from consideration of the continuity equations for electrons as

$$\frac{\partial n}{\partial t} = \nu n - \nabla \Gamma$$

... (1.51).

when "n" is the electron density, ν is the net production rate of electrons per electron and denotes the differences between the ionization rate and the attachment rate. Γ represents the electron current density lost to the walls by diffusion. The threshold for breakdown is considered to occur when $\partial n / \partial t$ goes through zero. The breakdown is then the characteristic value of the electric field obtained from the solution of the equation

$$\nu n - \nabla \Gamma = 0$$

... (1.52).

with the boundary condition that the electron density vanishes at the cavity surface. A high frequency ionisation coefficient can be defined as

$$\rho = \nu / DE^2$$

... (1.53).

where D = diffusion coefficient.

Values of β have been calculated by Brown and others from their breakdown measurements under parallel plate condition in cylindrical cavity and are expressed as function of E/p and $p\lambda$ where λ is the wavelength. The data are then used to calculate breakdown voltage in air between co-axial cylinders and results are found to be in close agreement with the experimentally determined values. If the applied frequency is greater than the frequency of inelastic collision and less than the frequency of elastic collision, Holstein (1946) showed that the energy distribution of electrons in a h.f. field is closely the same as that of electrons in a static field equal in magnitude to the r.m.s. value of h.f. field. Holstein deduced the breakdown condition that the rate of production of electron by ionisation must exceed the rate of loss due to diffusion for non attaching gases. In case of a uniform field between parallel plates the calculated relation between the breakdown gradient E , the gap length "d" and the gas pressure "p" is

$$(p \cdot d)^2 = \frac{\pi^2 K T_e}{e (E/p) \alpha/p} \dots (1.54).$$

α is the Townsend's first ionisation coefficient.

In a series of theoretical papers on h.f. discharge, Marganau and Hartman (1948) have discussed methods for determining the electron energy distribution and have shown how such functions can be used in the calculation of the breakdown fields on the assumption that the only mechanism for electron removal is recombination with positive ions. The calculated values are appreciably lower than the measured values and the discrepancy is explained by the consideration that electron must also be removed by other mechanism.

Kihara (1952) assuming a proper model for collision processes in the molecular kinetic theory of electrical discharge and modifying the Boltzman's transport equation obtained expressions for the fundamental parameters involved in the discharge phenomena of gases. Dividing the whole problem into different parts

Kihara obtained absolute expression for mobility coefficient, diffusion coefficient and electron temperature in terms of some molecular constants and some measurable parameters. The processes by which these molecular constants for different gases and vapours are to be calculated have also been provided. Starting from Boltzman distribution of charged particles in a gas with uniform temperature and pressure and nonuniform density and applied external electric field, Kihara (1952) also obtained the well known relation $\left[\text{diffusion coefficient} = \frac{K T_e}{e} \text{ mobility} \right]$ where T_e = electron temperature and K the Boltzman constant.

Assuming that the coefficient of elastic scattering between gas molecules and electron or ion is inversely proportional to the relative speed between the colliding particles an expression for the difference of gas temperature and electron temperature in terms of applied field and frequency has been obtained by Kihara. Extending this idea, the mobility coefficient of electron in gases is given by

$$\bar{K} = e/m N \lambda$$

... (1.5.5).

where

N = number of molecules per c.c. and λ is a molecular constant introduced by Kihara in this theory (dimension cm^3/sec). Kihara accounted for the excitation by electron with the help of a model giving crosssection of excitation as

$$Q(c_0, c) = P c^3 / c_0^2 \quad \text{i.e. which involves a process such that the}$$

speeds of electrons decrease from c_0 to values below c because of inelastic collisions. Here P is a molecular model constant with the dimension of area divided by velocity. According to this model the total cross-section

$$Q(c_0, c_0) = P c_0 \quad \text{is proportional to the speed of colliding electrons.}$$

For high frequency field, the electron temperature is obtained as

$$K T_e = \left(1 + \frac{\omega^2}{N^2 \lambda^2} \right)^{-1/2} \cdot \frac{1}{(3 \lambda P)^{1/2}} \cdot \frac{e E_0}{N \sqrt{2}}$$

and the dielectric constant

$$\epsilon = 1 - \frac{\omega_p^2}{(\omega^2 - j \omega N \lambda)}$$

The process of ionisation by collision with electron was explained assuming a model cross-section

$$Q = \begin{cases} \sigma (c^2 - c_i^2)^{3/2} / c_i c^2 & (c > c_i) \\ 0 & (c < c_i) \end{cases}$$

where σ is a molecular constant with the dimension of area and c_i corresponds to electron velocity at first ionisation potential. Since a few electrons with exceptionally large energies usually take the main part of ionisation, Kihara considered that the velocity distribution of electrons is not disturbed by the ionisation process so that it can be taken as Maxwellian. From this reasoning he obtained the expression for the first Townsend coefficient d as

$$d/P = A_0 \exp(-B_0 P/E)$$

where $A_0 = \frac{N}{P} \cdot \frac{\sigma}{c_i} \cdot \left(\frac{3 \lambda}{P} \right)^{1/2}$ and $B_0 = \frac{N}{P} \cdot \frac{m c_i^2}{2e} \cdot (3 \lambda P)^{1/2}$

When the gas is excited by microwaves and the pressure is high the loss of electrons is generally attributed to diffusion but in case of excitations by radiofrequencies the loss is due both to mobility and diffusion and the continuity equation in one dimensional treatment is given by

$$\frac{\partial n}{\partial t} = \nu n + D \frac{\partial^2 n}{\partial z^2} - [K E_0 \cos \omega t] \cdot \frac{\partial n}{\partial z}$$

where \bar{K} is the mobility coefficient of electron. The breakdown condition for r.f. discharge is

$$\frac{1}{\pi^2} \left(L - 2 \bar{K} E_0 / \omega \right) \frac{\nu}{D} = 1$$

which in explicit form can be written, on the assumption that electron's velocity distribution is Maxwellian, as

$$\exp\left(B.P/2E\right) = A_1 PL \left(1 - \frac{E/B.P}{C_2 L/\Lambda}\right) \dots (1.56).$$

where A_1 and C_2 are two derived molecular constants introduced by Kihara Λ is the wavelength of the applied r.f. field. This theoretical expression is in agreement with the experimental observations upto a certain limited range. Taillet and Brunet (1965) in their conference paper investigated the physical mechanism of high frequency discharges maintained by resonance. It was concluded that when a radiofrequency discharge is excited with a frequency $\omega/2\pi$ higher than the collision frequency ν , a resonance due to the dispersive properties of the plasma can control the steady state of the discharge and determine the value of the electron density for a given geometry and frequency.

Besides the two general type of loss of electrons in high frequency discharge namely mobility and diffusion, there may be a third type of loss mechanism which becomes very prominent in case of certain gases. This is the loss by formation of negative ion. Negative ions appear in gases under two circumstances, (a) they may be created in the gas largely through attachment of free electrons to atoms and molecules and rarely by dissociation of molecules in the polar phase by electron impact, (b) they may be introduced in the gas by interaction of fast particles of atomic mass with surfaces or by liberation from hot surfaces. Attachment of electrons causes loss of the former as ionising agents and leads to delayed and undesirable electronic ionising events in asymmetrical field breakdown. It may be further act to increase the rate of loss of carriers by recombination.

This loss of electron by attachment is ^avery predominant factor in case of certain types of gas e.g. O_2 , CO_2 , SO_2 , halogens, some organic vapours etc.

which have a strong affinity to attach the electrons to neutral atoms or molecules to form negative ion directly or by dissociation. The electron is bound to the molecule with an energy ϵ_a with is called the electron affinity. The phenomenon of electron attachment to neutral atom is a common occurrence for gases whose outer electronic shells are nearly filled. The measure of the ease with which an electron can attach to a neutral atom or molecule is given by the electron affinity energy which varies from about 4 volts for gases like F and O_2 to nearly zero for those gases which exhibit small attachment and is -ve for those which do not. Atoms characterised by closed electronic shells are inert to extra atomic electrons. Molecules in a Σ ground state are characterised by no resulting spin or angular momentum. Their electrons form closed groups and hence also show inertness to extra molecular electrons. Gases such as H_2 , N_2 and CO fall into this group and show no electron attachment.

The attachment of electrons in gases was not clearly perceived until about 1910 when the vacuum techniques and gaseous purification of gases let Franck and Rohl (1910) to study ion mobilities in inert gases and N_2 and they noted the presence of free electrons at higher pressures. The studies of Townsend (1914) and his co-workers Lattey, Tizzard (1912) had led to the recognition of the existence of free electrons at lower pressures in gases. The experimental works leading to the ultimate discerning of electron attachment were studies of the variation of carrier mobilities in air as a function of pressure by A.F. Kovarick (1910) with the Rutherford A.C. method of mobility measurements using photo electrons and those of E.M. Wellisch (1915, 1916, 1917) using the same method but producing ions by α - particles from PO in an auxiliary field below a gauge following the method of Franck.

Observation of Wellisch may be stated briefly in the following words. The separation previously effected between the electrons and the negative ions in

dry air at lower pressures has been further extended to CO_2 and H_2 as in these two gases the electrons are relatively more numerous than in air at the corresponding pressure. A trace of impurity is especially effective in reducing the number of free electrons when the gas is at relatively high pressure; at low pressure the effect of impurity is less marked. In most cases a velocity greater than that arising from thermal agitation at ordinary temperature appears to be necessary to enable the electron to effect a permanent union with an uncharged molecule of the gas or impurity. For the vapour of petroleum ether, whose molecules contain only atoms of carbon and hydrogen, the negative carriers appear to consist practically entirely of free electrons; a trace of impurity, however is sufficient to effect the production of a considerable number of negative ions. A brief investigation has been made of the motion of the free electrons through CO_2 ; the results do not indicate that the velocity of the electron is proportional to the applied field, but suggest that the electron may traverse a considerable distance with accelerated motion before its terminal velocity is acquired. In no instance was any evidence obtained of a change in the nature of either the positive or negative ion as the pressure of the gas was reduced. The present method was employed to determine the values of the ionic mobilities for a few vapours and the results have been compared with previous determinations. Loeb (1921, 1923, 1924) in a series of work investigated the possible theories of formation of negative ion from electron and neutral molecules proposed by J.J. Thomson and by Wellisch. Mobilities of the carriers formed by photo electrons liberated from one plate of a parallel plate condenser by a beam of ultra violet light, focussed on it at a glancing angle from a quartz lens, were determined at different pressures for air using the Rutherford A.C. method. The results in general confirmed the results of previous observers, yielding a single class of carriers

whose mobilities became abnormal below 150 mm. pressure. The values of these mobilities were also found to be a function of the frequency of commutation in agreement with earlier results. The manner of introduction of ultraviolet light into the chamber reduced the stray light effect and it was found that the asymptotic feet of the curves observed below 200 mm. pressure were a real and important feature of the phenomenon. The mathematical theory of J.J. Thomson was adapted to fit these measurements and on the basis of the equation so deduced the chance of ion formation " n " was determined from experiment. Within the limits of accuracy of the method, " n " was found to be equal to about 2.5×10^5 for pure dry air. The current voltage curves computed on the basis of the Thomson theory were compared with the observed curves and marked general similarities were noticed below 200 mm. pressures. The asymptotic feet of the computed and observed curves lie close together, which is significant in as much as it is these portions of the observed curves that yield the abnormal values of the mobility. Deviations of the observed curves from those computed at the higher and lower pressures are explained. Repetition of the Wellisch experiments shows that what he termed "free electrons" are the carriers of abnormally high mobilities observed by the earlier workers. It is shown that as the electrons do not attach to N_2 molecules, and that as the values of " n " obtained in pure O_2 and in N_2 with small quantities of O_2 in it agree with the values found for air on the basis of its oxygen content, one must conclude that it is to the O_2 molecules in air that the electrons attach. The value of " n " for O_2 molecules is then 5×10^4 .

Most of the methods of measurements of " h ", the attachment probability were handicapped due to different reasons. Because of the very low values of " h " in many gases, as well as the difficulty of achieving groups of electrons of narrow energy spread in gases of sufficient density for appreciable attachment, significant studies on the appearance potentials of ions and energy of ion formation with

identification of ion species formed by mass spectrographs have not been successful, until when Hickam and Fox (1954) applied their retarding potential difference method to the study of attachment of electrons to SF_6 combined with mass spectrograph revealing a new technique of investigation.

As electron that makes ν_c impacts per sec and under the action of the field "E" moves μE centimeters per sec. takes $1/\mu E$ seconds to go one centimeter. Starting with "n" electrons, the number dn out of "n" that attach in going dx centimeters will depend on "n", $\nu_c/\mu E$ and on dx . If "h" is the proportionality constant, then $dn = -h n \nu_c \cdot dx/\mu E$. "h" is called the probability of attachment and is the reciprocal of the average number of impacts an electron makes to attach and μ is the mobility coefficient. Another quantity " β " may be defined as the probability of attachment per cm. travel in analogy to ionisation coefficient " α " and likewise β/p is a function of E/p . These two attachment coefficients are related by $h = \beta \mu E/\nu_c$. Hence another coefficient ν_a may be defined in analogy to ν_i , ionisation frequency, and may be called the attachment frequency and it is related to "h" by $h = \nu_a/\nu_i$. Taking into consideration this new mechanism, the continuity equation for number of electrons / c.c. may be modified by putting $[(\nu_i - \nu_a) n]$ in place of $(\nu_i n)$ as the frequency of production of electrons, when the breakdown condition in case of high frequency discharge with Maxwellian velocity distribution of electron gas is given by $\frac{\alpha}{p} = \frac{\beta}{p} - \frac{2}{3} \frac{\pi^2 U_{ave}}{(E_c/p)(p.d)^2}$ where E_c = effective field, U_{ave} = average electron energy in e.v. The quantities α/p , β/p and U_{ave} are all functions of E_c/p and depend on the energy distribution function. Different authors measured the variation of α/p and β/p with E/p . Considering different possibilities of energy dissipation of electron after attachment to the molecules and atoms and applying continuity equation Harrison and Geballe (1953) obtained the expression for D.C. current for applied d.c. voltage E as

$$i = i_0 \left[\frac{\alpha}{\alpha - \beta} \right] \exp \left[(\alpha - \beta) d \right] - i_0 \frac{\beta}{\alpha - \beta} \dots (1.57)$$

where

d = distance between the electrodes. Variation of d.c. current with different electrode separation for values of $E/p = 60$ to $E/p = 25$ volts/cm. mm. of Hg. were obtained. Variations of β/p with d/p were obtained for air, Freon, CF_3 , SF_3 . Measurements of variation of "h" with E/p were made by Bradbury and Tatal (1934) for gases SO_2 , H_2O , H_2S , NH_3 , H_2O , HCl , Cl_2 and different mixtures of attaching gases. Burch and Geballe (1957) measured the variation of β/p with E/p of oxygen. Measurements of cross section of attachment of halogens Cl_2 , Br_2 , I_2 for different energy of the electron by Healey (1938) show a maximum near 2 volts of energy of electrons for all three gases. These are the some of the observations of variation of β/p with E/p .

These measurements of variation of β/p and d/p with E/p help to compare the breakdown voltage data observed in high frequency discharge of attaching gases taking the effective high frequency field as the applied D.C. field. Harlin and Brown (1948) measured the breakdown voltage in air at 3000 Mc/sec with the distance varying from 0.635 cm. to 0.153 cm. and the pressure varying from 70 mm. Hg. to 2 mm. Hg. Similar measurements were done by Pim (1949) at 200 Mc/sec. with the gap length varying from 0.08 cm. to 0.06 cm. and the pressure varying from 760 mm. Hg. to 160 mm. Hg. The discrepancy between these observations and theoretical plot of breakdown curve, obtained by taking help of measurements of Healey and Read (1941) for average electron energy as a function of E/p was of the order of 10%. However with increased purity of air-by taking every observation with fresh air after exhausting all air of the previous observation- the experimental curve shows much better agreement with the theoretical curve. The data of microwave

breakdown measurements in oxygen at 3000 Mc/sec with gap length 0.635 cm. over a range of pressures from 70 to 2 mm. Hg. of them are in good agreement with the theoretical value calculated with the help of measurements of α/p and β/p for oxygen from the work of Harrison and Geballe (1953) and taking the value of $\nu_m = 3.5 \times 10^9 p$ obtained from mobility measurements of Nielsen and Bradbury (1937) and the relation for the a.c. mobility, to get the value of E_c given by

$$E_e^2 = \frac{E_p^2}{2} \frac{\nu_m^2}{\nu_m^2 + \omega^2} \quad \text{where} \quad \dots (1.58).$$

$E_p \exp(j\omega t)$ is the applied field (high frequency) and ν_m is the collision frequency.

Breakdown in presence of magnetic field.

Breakdown of a high frequency discharge in a gas in presence of magnetic field has been studied previously by some workers. Townsend and Gill (1937) calculated the effect of a magnetic field on the breakdown potential of a gas under r.f. excitation and showed that the mobility of the electrons in the direction of the electric field is reduced and is given by the equation

$$\bar{K}_H = \frac{\bar{K}}{1 + \omega_H^2 \tau^2} \quad \dots (1.59).$$

where $\omega_H = eH/mc$ the cyclotron frequency,

and τ is the time between successive collisions. The diffusion coefficient D is reduced in a direction perpendicular to the magnetic field in the ratio

$$D_H = \frac{D}{1 + \omega_H^2 \tau^2} \quad \dots (1.60).$$

From these considerations, they observed that if the electric and magnetic fields are parallel, the diffusion perpendicular to the field is reduced and hence a

smaller breakdown field is necessary. If the fields are perpendicular, not only the breakdown voltage is reduced but for certain value of the magnetic field and the applied frequency resonance will occur when

$$f_{\text{applied}} = \frac{eH}{2\pi mc} \dots (1.61)$$

They carried out experiments in air for two frequencies namely 48 Mc/sec and 30 Mc/sec. and the range of pressure varying from a few mm.Hg. to 24 mm. of Hg. A decrease of the starting potential was noted for values of pressure less than the minimum without field and increase of starting potential for values of pressure greater than that at which the breakdown voltage becomes minimum when the magnetic field is applied. The values of the magnetic field were so chosen that the resonance condition was satisfied. The work has further been extended by Brown (1940) to the case of hydrogen who obtained almost similar results.

Iex, Allis and Brown (1950) carried out experiments on the breakdown voltage of a gas excited by a microwave field in presence of a transverse magnetic field. The gas used was helium containing a small admixture of Hg. vapour and they obtained breakdown curves for different values of pressure. The breakdown voltage becomes a minimum for a magnetic field (1125 gauss) for all values of the pressure, the effect of resonance being most marked at low values of pressure.

Ferritti and Veronesi (195) performed experiments in air for frequencies ranging from 10 Mc/sec to 30 Mc/sec. in air, the magnetic field varying from 0 to 600 gauss. They used cylindrical electrodes and observed a lowering of breakdown potential in presence of magnetic field.

Most of the works in this line were done in resonance magnetic field such that the frequency of the applied field and the magnitude of the magnetic field are of such a value that $f_{\text{applied}} = \frac{eH}{2\pi mc}$ was satisfied. So far practically

little work has been done in which the magnetic field is far removed from the resonance value. Sen and Ghosh (1963) studied the breakdown in air and nitrogen in crossed nonresonant magnetic field applying the radiofrequency voltage of frequency 8.1 Mc/sec. and 7.15 Mc/sec. respectively in the pressure range of a few microns Hg. to 500 micron Hg. They obtained a family of curves for different steady magnetic fields whose value lies within 100 gauss. It was observed that each curve for a steady crossed magnetic field has got a minimum breakdown voltage at a certain pressure which shifts to higher pressure as the magnetic field is increased. An increase of breakdown voltage was also observed on the application of transverse magnetic field within the range of pressure for which the measurements were taken. Following the theory of Kihara (1952) for breakdown of gases by radiofrequency field and equivalent pressure concept introduced by Blevin and Haydon (1950 with the variation of mobility and diffusion coefficient in a magnetic field, an expression for the breakdown voltage of gases by r.f. field was developed to explain their experimental results. It was observed that the theoretical results are in fairly good agreement with experimental results. The discrepancy was attributed to uncertainties in the values of molecular constants introduced by Kihara in his theory. They also considered the effect of attachment loss to the breakdown condition and obtained the modification in their breakdown voltage expression as

$$E_0 = \left(E_0^a \right) \cdot b + \frac{L \omega (1-b)}{2 \bar{K}} \quad \dots(1.62).$$

$$b = \left[\frac{\nu_i - \nu_a}{\nu_i} \right]^{1/2} - \left[\frac{\alpha/P - \beta/P}{\alpha/P} \right]^{1/2} \quad \text{where}$$

and \bar{K} = mobility coefficient;

L = length of the gap; ω = applied frequency.

E_0 = breakdown voltage without consideration of attachment.

E_e = breakdown voltage with consideration of attachment.

This new modification with the consideration of attachment loss showed a better agreement between theoretical and experimental breakdown voltage.

Sagnall and Haydon (1965) studied the pre-breakdown ionisation in molecular nitrogen to establish whether the influence of a transverse magnetic field is equivalent to an increase in the gas pressure from " p " to $P_e = P(1 + \omega^2/\nu^2)^{1/2}$ where " ω " is electron cyclotron frequency, and ν a constant, which is the effective electron molecule collision frequency. When the value of E/P_e lies within the range $150 < E/P_e < 250 \text{ V cm}^{-1} \text{ Torr}^{-1}$, ν has a constant value equal to $8.3 \times 10^9 \text{ P sec}^{-1}$ but when $E/P_e < 150$, ν/P must decrease with decreasing E/P_e for satisfactory agreement to be maintained. The possibility of extending the concept to account for the changes in secondary ionisation and the breakdown potential in nitrogen are also discussed. Considering the different complex situations of pre-breakdown ionisation at different range of E/P_e , they observed that the complex situation is not restricted to nitrogen so that an approach to the problem of breakdown in terms of an equivalent increase in gas pressure is by no means simple and at least for nitrogen the equivalent pressure concept is valid within a limit range of E/P_e value.

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